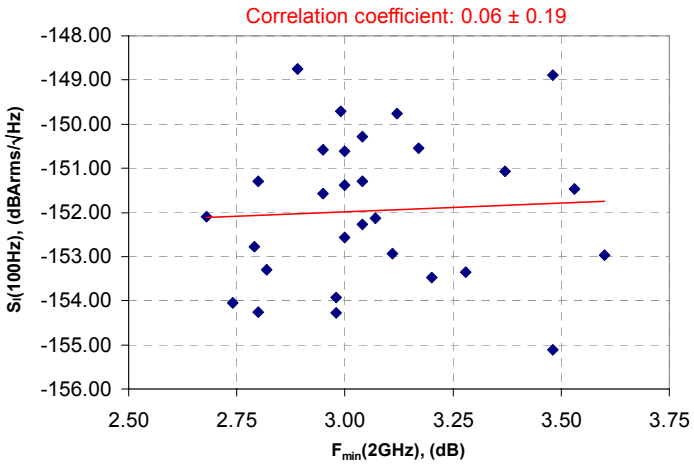
UNIVERSITÄT STUTTGART
INSTITUT FÜR ELEKTRISCHE UND
OPTISCHE NACHRICHTENTECHNIK
PROF. DR.-ING. MANFRED BERROTH
PFAFFENWALDRING 47
70569 STUTTGART
DEUTSCHLAND

RENSSELAER POLYTECHNIC INSTITUTE
ELECTRICAL, COMPUTER AND
SYSTEMS ENGINEERING DEPARTMENT
PROF. MICHAEL SHUR
110 8TH STREET
TROY, NY 12180
USA



CORRELATION BETWEEN THE FLICKER AND THE MICROWAVE NOISE OF GALLIUM NITRIDE HETEROSTRUCTURE FIELD EFFECT TRANSISTORS

TOBIAS WERNER

ELECTRICAL ENGINEERING
UNIVERSITY OF STUTTGART
MATRIKELNUMMER 1710551
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ABSTRACT

The correlation between the low frequency flicker noise and the microwave noise at room temperature of gallium nitride (GaN) heterostructure field effect transistors (HFETs) is investigated.

The study is based on a comparison between the noise levels of the microwave and the flicker noise. The minimum noise figure F_{min} at 2 GHz represents the microwave noise and the spectral voltage noise density S_V, the spectral current noise density S_I, the relative spectral current noise density S_I / I^2 or the Hooge parameter α_H at 100 Hz expresses the flicker noise.

Both noise types are functions of the applied voltages at the gate and drain of the transistor, but show different behavior. Whereas the optimum bias condition for lowest microwave noise is in saturation and the noise in the linear region of the transistor is considerably higher, it behaves in reverse with the flicker noise.

Due to this bias dependence three approaches are chosen to analyze a possible dependence between the two dominant types of noise in the microwave and low frequency domain:

1) *Lowest noise*: F_{min} in saturation is compared to S_V, S_I, S_I / I^2 and α_H in the linear region for several transistors.
2) *Identical bias condition*: F_{min} is compared to S_V and S_I for an *identical* bias condition in saturation for several transistors.
3) *Entire bias range*: F_{min} is compared to S_V and S_I for an identical bias condition for one transistor and several bias conditions. This method was also carried out for F_{min} at additional frequencies of 10 GHz and 26 GHz.

With the aid of the correlation coefficient the dependence of the two noise types is evaluated and scatter diagrams are used to verify graphically the calculated result.

The spectral current noise density S_I appears to be the most expressive parameter to refer to the flicker noise and correlation coefficients between 0 and -0.3 with an absolute error of ±0.2, due to a small number of observations, are obtained. The small correlation coefficient is supported by a widely spread point constellation, covering the entire plot area of the scatter diagrams, which shows no dependence between the flicker and the microwave noise.

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1 INTRODUCTION

Electronic devices and systems exhibit random fluctuations in the voltage or current at their terminals, and these fluctuations are usually referred to as *noise*. Noise is present in every electronic system and is unwanted because it limits its performance.

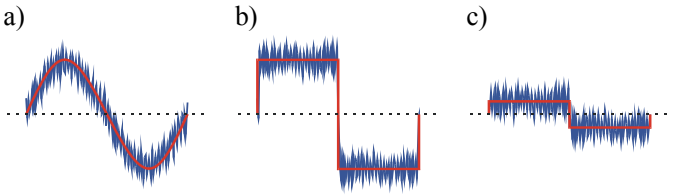


Fig. 1.1: Noise distorting (a) an analog signal (b) a regeneratable digital signal, and (c) a non-regeneratable digital signal.

In analog systems noise distorts a processed signal (*Fig. 1.1a*) and cannot be separated from it because of the non-deterministic nature of noise. As a result the signal-to-noise ratio of an amplifier chain decreases since not only the signal but also the noise is amplified and every stage adds its own noise contribution. In digital systems the signal (*Fig. 1.1b*) can be regenerated but the importance of noise becomes more and more significant as the trend to lower supply voltages continues (*Fig. 1.1c*). Thus the reduction of noise is important for both analog and digital systems.

Electronic noise may be conveniently divided into two categories determined by the noise source. In the first category the noise source is *external* to the device under consideration. In the second category the noise is generated *within* the circuit element and is called *intrinsic noise*.

This work investigates the intrinsic noise behavior of the basic component of electronics, semiconductor devices. Several aspects, like device geometry or material quality affect the noise level of transistors. In order to understand the complex interplay between these parameters and to be able to reduce the noise, the underlying physical phenomena have to be studied and understood. Often only the assistance of simulation tools can help to gain an idea about the interaction of different noise origins, but this requires valid noise models.

The dependence of two noise types, namely the *flicker* or *1/f -noise* and the *microwave noise*, of gallium nitride (GaN) heterostructure field effect transistors (HFETs) at room temperature was studied.

Whereas the microwave noise originates in thermal fluctuations of electrons the experts still lead controversial discussions about the origins of flicker noise. For GaN HFETs with the electron transport in the two-dimensional electron gas a possible explanation is that traps in the space-charge region under the gate generate the flicker noise. The trapping and detrapping of electrons gives rise to a 1/f modulation of the channel conductance, and this produces flicker noise in the drain current [1].

The flicker and the microwave noise are the dominant sources of noise in the low frequency and microwave region, respectively. The demand of industry goes to ever increasing frequencies and one could wonder, why it is important to analyze low frequency noise. This is due to the fact, that the low frequency noise is up-converted to a higher frequency band and can there interfere with the main signal, if, for example, a transistor is applied in an oscillator circuit [2].

GaN is a new promising material combination, especially for high power applications, due to its higher breakdown voltage in comparison to the state-of-the-art technology, gallium arsenide (GaAs). For GaN semiconductors a share of the market of 3 billion dollars was forecasted for the year 2006[1].

The expression *heterostructure* denotes that a wide band gap semiconductor layer (AlGaN) is brought together with a narrow band gap semiconductor layer (GaN). Due to the difference in electron affinities of these two layers a two-dimensional electron gas (2DEG) is formed at the so-called heterointerface, what results in an improved electron mobility and electron velocity.

With the result of this investigation important conclusions can be drawn concerning the noise mechanisms in semiconductors. This can help to improve noise models and thus to better predict the noise performance of semiconductors.

The measurement process to determine the minimum noise figure is more complex and thus more time consuming than the characterization of the flicker noise. Therefore, if dependence between the flicker and the microwave noise could be found, quicker noise determination of analyzed devices could be performed.

In ***Chapter 1*** we will introduce different kind of noise with a focus on *flicker noise* and *microwave noise*.

Chapter 2 will give a brief overview about the analyzed transistors, their characteristics and typical device performance.

To characterize the noise properties of the transistors in the low frequency and the microwave region two different measurement setups were used and will be presented in ***Chapter 3***.

In ***Chapter 4*** the obtained measurement results for the flicker and the microwave noise will be discussed and examined for a possible correlation.

In ***Chapter 5*** we will compare and summarize the obtained results and draw a conclusion.

In the ***Appendix*** explanations of the used symbols and abbreviations, long derivations, specific waver information, program listings, and the references can be found.

[1] III-Vs, *vol 11, No 1, p. 7*, Jan-Feb 1998

2 NOISE

Noise arising in an electronic component or a device is historically classified as *thermal noise*, *shot noise*, or *flicker noise*.

Thermal noise occurs in any conductor due to the random motion of electrons caused by thermal agitation. In 1928 Johnson experimentally verified Schottky's theory that the thermal noise voltage depends only on resistance, temperature and bandwidth and is independent of material and shape [3]. Because of this discovery thermal noise is also called *Johnson noise*. At the same time H. Nyquist showed that the available noise power is always $k \cdot T \cdot B$, where B is the equivalent noise bandwidth, T the absolute temperature and k the Boltzmann constant [4].

Shot noise and flicker noise, which are also called *excess noise* as a generic name, are present only when current flows through a conductor by an external means. Flicker noise is influenced by surface state and bulk imperfection and cannot be described by simple physical explanations as thermal noise. Since flicker noise has a $1/f^{\gamma}$ dependence with γ close to unity, this noise is often called *1/f-noise*.

The dominant noise types in GaN HFETs are the flicker noise in the low frequency range and the microwave noise for elevated frequencies in the microwave range. The flicker noise is often overlaid by the so-called *generation recombination noise (GR-noise),* which is caused by fluctuations in the number of free carriers and can be related to the presence of trap centers in the forbidden gap [5].

2.1 Flicker noise or 1/f-noise

When current passes through a resistor or a semiconductor, noise is generated in excess of the thermal noise in a resistor or the thermal noise plus the shot noise in a semiconductor. This excess noise has a spectral density, which increases, as the frequency decreases and, because it is most noticeable at low frequency, it is also known as *low frequency noise*. In addition, it is known as *flicker noise* because of the flickering of a the needle on a meter measuring the current with a significant component of this type of noise, and used to be known as *semiconductor noise* since the noise in early semiconductor devices was dominated by this type [6].

Numerous scientists have investigated the phenomenon of flicker noise in semiconductor devices but the details of the mechanisms involved are still not entirely understood. There is no consensus to the origin of the 1/f-noise and it is very likely that there exist more than one mechanism, giving rise to the same noise characteristics.

It appears that 1/f-noise can be a surface effect and a bulk effect and the physical origins of the noise presumably being different in the two cases.

According to McWhorter's number fluctuation theory [7], 1/f-noise is attributed to the trapping and detrapping processes of the charges in the oxide traps. Hooge's empirical model [8] considers the 1/f-noise as a result of carrier mobility fluctuation due to lattice scattering. It has been reported that both the carrier number fluctuation and the mobility fluctuation are possible mechanisms, which lead to the 1/f-noise.

The 1/f-noise in HFETs was at first rather large, extending to 1 GHz. It varied as $I_d{}^2$ at low drain currents. The 1/f-noise seems to be generated by traps in the space-charge region under the gate. The trapping and detrapping of electrons gives rise to a 1/f modulation of the channel conductance, and this produces 1/f-noise in the drain current. It is not quite clear how trapping and detrapping of electrons in the space-charge region can give a 1/f modulation; a distribution in time constants might be responsible [1].

For HFET devices with carrier transport exclusively in the 2DEG, it seems reasonable, that the hetero interface contributes to the noise by exchanging electrons with the channel [9].

Flicker noise depends on many parameters like temperature, frequency, bias condition, device geometry, or material characteristic (doping level, layer structure and thickness, etc.). The noise level can be expressed by the spectral voltage noise density S_V, the spectral current noise density S_I, the relative spectral current noise density S_I / I^2 or by the dimensionless Hooge parameter α_H.

2.1.1 The Hooge parameter

Hooge proposed in the late 1960s that *1/f* fluctuations in all homogeneous materials could be represented by the empirical formula [10]

$$\frac{\overline{S_r(\omega)}}{R_0^2} = \frac{\alpha_H}{N_{tot} \cdot |f|}, \tag{2.1}$$

where N_{tot} is the total number of charge carriers in the specimen, R_0 is the mean resistance, $\overline{S_r(\omega)}$ is the power spectral density of resistance fluctuations, and $\alpha_H \approx 2.0\text{E-}3$ is a universal constant.

Later experiments showed that the Hooge parameter is not constant, but can vary between several orders of magnitude. α_H of GaN devices lies in a range of about 1.0E-5 to 1.0E-1 [5], [11]. The Hooge parameter can also be written as [12]

$$\alpha_H = \frac{S_I}{I_d{}^2} \cdot f \cdot N, \tag{2.2}$$

with N the number of carriers and I_d the drain source current and can be used to express the noise level of a transistor for low drain biases.

As mentioned before, equation (2.2) is only valid for homogenous materials. If high drain source voltages are applied to the device, the electron distribution in the channel gets inhomogeneous and the use of the Hooge parameter is questionable. Furthermore, the flicker noise is proportional to $I_d{}^2$ in the linear region of the transistor, i.e. for low drain source voltages. Therefore the flicker noise is often normalized to I^2 and also the Hooge parameter normalizes on this parameter. In saturation however, i.e. for elevated drain source voltages, the flicker noise is no longer proportional to the squared drain source current and the normalization and with it the use of the Hooge parameter to express the noise level of the transistor gets again doubtful.

The Hooge parameter α_H takes into account different drain source spacings of compared transistors by the estimation of the number of carriers N in the source-drain-region. N can be calculated by

$$N = w \cdot \ell \cdot n_s \,, \tag{2.3}$$

with the electron sheet density n_s, which is determined by measurement, the gate width w, and ℓ, the spacing between source and drain (*Fig. 2.1*).

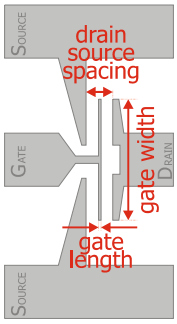


Fig. 2.1: Dimensions of a transistor.

2.2 Microwave noise

A field effect transistor (FET) can be considered as a voltage controlled resistor. Thermal noise of this resistor, the channel, plays the dominant role in the microwave region, where the flicker and GR-noise vanishes.

The microwave noise is a function of temperature, frequency, bias condition, device geometry, or material characteristics and depends further on the source reflection coefficient Γ_s. The noise level is usually characterized by the noise figure F in dB.

2.2.1 Theory of microwave noise measurement

The noise figure of linear two-ports is a function of the source admittance [13]. The general equation expressing the noise figure of a network as a function of source reflection coefficient Γ_s is

$$F = F_{min} + \frac{4 \cdot R_n}{Z_0} \cdot \frac{\left|\Gamma_s - \Gamma_{opt}\right|}{\left|1 + \Gamma_{opt}\right|^2 \cdot \left(1 - \left|\Gamma_S\right|^2\right)}, \tag{2.4}$$

where Γ_{opt} is the *complex source reflecting coefficient* that results in the *minimum noise figure* F_{min} of the network, Z_0 is the *reference impedance* for defining Γ_s (usually 50 Ω) and R_n is called the *equivalent noise resistance* and is an empirical constant with the dimension of a resistance, relating the sensitivity of the noise figure to the source admittance. The noise properties of a device are fully characterized by these four noise parameters.

To find F_{min}, Γ_{opt} and R_n the noise figure F must be measured at a variety of source impedances. In principle, since four scalar variables (Γ_{opt} is complex!) are to be found, only four measurements are required. In practice, however, more points are measured, and a least mean square technique is applied to extract the parameters from the over-determined data.

Noise characterization also requires the parameters of the device under test (DUT) to be separated from the parameters of the measurement system, to which the DUT is connected. To do this, the system must be calibrated to compensate the system contribution.

The noise contribution of the system (often called the second stage since it follows the DUT) will vary with its source impedance according to (2.4). Therefore, the complete noise and gain parameters of the system must be known to determine the system noise contribution when a particular DUT is connected. This consists of measuring the total noise figure, F_{total}, with several different source impedances. The noise figure F_{dut} of the DUT for each position is then given from the Friis's cascade equation [14] in (2.5).

$$F_{dut} = F_{total} - \frac{F_{sys} - 1}{G_{dut}} \tag{2.5}$$

G_{dut} is the available gain of the DUT and is resolved from the DUT's S-parameters and the source reflection coefficient.

3 ANALYZED TRANSISTORS

The first Field Effect Transistor (FET) was already proposed in 1930 by Lilienfeld. The FET is a three-terminal device in which the current through two terminals (*source* and *drain*) is controlled by a voltage at the third terminal (*gate*). It is a majority carrier device and is therefore often called a unipolar transistor.

The FET comes in several forms. In a Junction Field Effect Transistor (JFET) the control gate voltage varies the depletion width of a reverse-biased p-n junction. A similar device results if the junction is replaced by a Schottky barrier (MEtal Semiconductor Field Effect Transistor, MESFET). Alternatively the metal gate electrode may be separated from the semiconductor by an insulator (Metal Insulator Semiconductor Field Effect Transistor, MISFET). The Metal Oxide Semiconductor Field Effect Transistor (MOSFET) is a common special case of this type and uses an oxide layer as the insulator.

Since the MESFET is compatible with the use of III-V compounds, it is possible to exploit the band gap engineering available with heterojunctions in these materials. In order to maintain high transconductance in a MESFET, the channel conductivity must be as high as possible. Increasing the doping in the channel and thus the carrier concentration increases the conductivity. However, increased doping also causes increased scattering by ionized impurities, which leads to a degradation of mobility. What is needed is a way of creating a high electron concentration in the channel of a MESFET by some other means than doping. An approach to this requirement is to grow a thin undoped well (e.g. GaN) bounded by wider band gap, doped barriers (e.g. AlGaN). This configuration, called *modulation doping*, results in conductive GaN when electrons from the doped AlGaN barrier fall into the well and become trapped there. Since the donors are in the AlGaN rather than the GaN, there is no impurity scattering of electrons in the well. This device is called a MOdulation Doped Field Effect Transistor (MODFET) or High Electron Mobility Transistor (HEMT). It is also called Heterostructure Field Effect Transistor (HFET), Two Dimensional Electron-Gas Field Effect Transistor (TEGFET) or Selectively Doped Heterostructure Field Effect Transistor (SDHFET).

When two different semiconductors layers are joined together, the atoms at the interface have to form chemical bonds. Due to a difference in the electron affinity of these two layers a two dimensional gas (2DEG) is formed at the so-called heterointerface.

In HFET a wide band gap semiconductor layer separates the gate from the channel (*Fig. 3.1*). At the heterointerface between the wide and narrow band gap semiconductor layers a 2DEG is formed and carries the drain-to-source current.

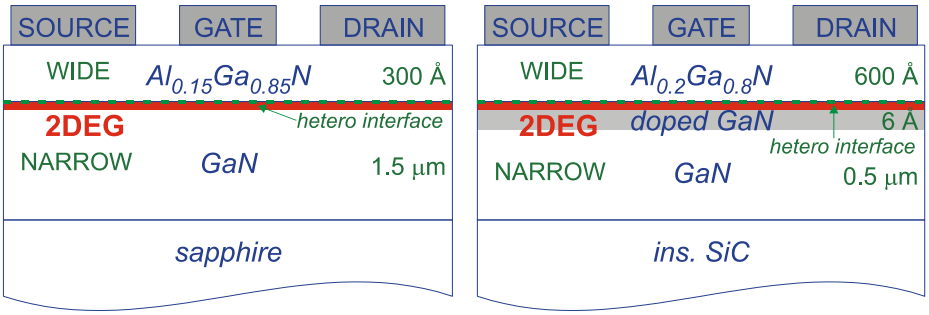


Fig. 3.1: Examples of modulation doped layers for HFETs.

All analyzed devices were AlGaN/GaN HFETs with an aluminum mole fraction of 15 to 20 percent and were grown on a sapphire or SiC substrate.

The devices were processed in collaboration with Cornell and the University of California Santa Barbara and were fabricated with a Metal Organic Chemical Vapor Deposition (MOCVD). The surface was non-passivated.

The carrier sheet density was in the order of 1.1E+13 cm^{-2} and the mobility varied between 1000 and 1400 $cm^2/V/s$.

All transistors had a T-shaped gate (*Fig. 3.2*) with a quarter micron gate length and 100 micron gate width.

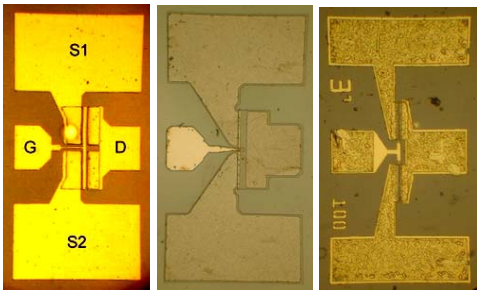


Fig. 3.2: Examples of GaN HFETs with T-shaped gate.

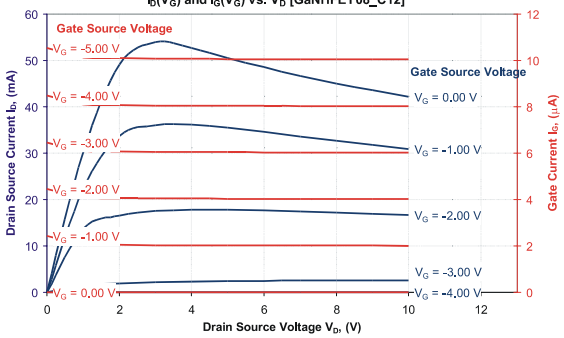
The waver maps, which describe the location of the analyzed transistors on different wafers, and specific layer structures and parameters, can be found in *Appendix D: Waver information*.

3.1 Typical device performance

Measurement results vary from transistor to transistor and from waver to waver due to the complex fabrication process. Numerous transistors on four different wavers were examined and the following graphs represent typical measurement results.

In *Fig. 3.3* a current voltage characteristic of a GaN HFET is compared to that of a GaAs Pseudomorphic High Electron Mobility Transistor (PHEMT). The drain source current I_D and the gate current I_G are plotted versus the drain source voltage V_D for different gate source voltages V_G. The GaN HFET can stand much higher drain source voltages due to the elevated breakdown voltage of GaN devices [15]-[17], what can be noticed by the increased drain voltage range in *Fig. 3.3a*. While the slope in saturation of the output characteristic ($I_D(V_G)$ vs. V_D) in saturation is positive for GaAs devices (*Fig. 3.3b*), it shows typically a negative tendency for GaN HFETs (*Fig. 3.3b*).

a)


ID(VG) and IG(VG) vs. VD [GaNHFET08_C12]
Gate Source Voltage
VG = -5.00 V
VG = -4.00 V
VG = -3.00 V
VG = -2.00 V
VG = -1.00 V
VG = 0.00 V
Gate Source Voltage
VG = 0.00 V
VG = -1.00 V
VG = -2.00 V
VG = -3.00 V
VG = -4.00 V
Drain Source Current ID, (mA)
Gate Current IG, (µA)
Drain Source Voltage VD, (V)

b)

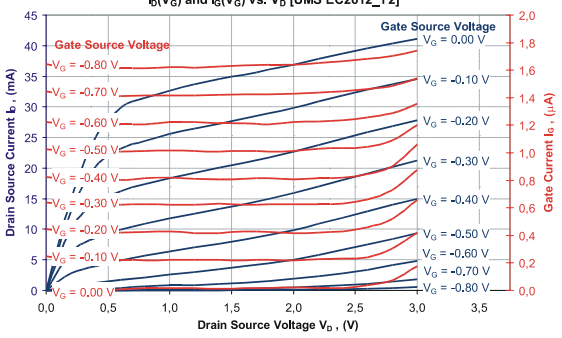

ID(VG) and IG(VG) vs. VD [UMS EC2612_T2]
Gate Source Voltage
VG = -0.80 V
VG = -0.70 V
VG = -0.60 V
VG = -0.50 V
VG = -0.40 V
VG = -0.30 V
VG = -0.20 V
VG = -0.10 V
VG = 0.00 V
Gate Source Voltage
VG = 0.00 V
VG = -0.10 V
VG = -0.20 V
VG = -0.30 V
VG = -0.40 V
VG = -0.50 V
VG = -0.60 V
VG = -0.70 V
VG = -0.80 V
Drain Source Current ID, (mA)
Gate Current IG, (µA)
Drain Source Voltage VD, (V)

Fig. 3.3: Typical current voltage characteristic of (a) GaN HFETs in comparison to (b) GaAs PHEMTs.

The gate current is often referred to as the *gate leakage current*, because ideally it should be zero for field effect transistors. The HFET devices show a low gate leakage current in the range of µA, what is especially important for low flicker noise [12].

Fig. 3.4 shows typical S-parameters of a GaN HFET from 2 GHz to 10 GHz for a bias condition of V_D = 10 V and V_G = -0.5 V. The S-parameters S_{11} and S_{22} are typically presented in a smith chart (lower half of *Fig. 3.4*) and S_{12} and S_{21} in a polar chart (upper half of *Fig. 3.4*). Nearly all measured devices demonstrated a S_{21} smaller than unity at a reference system impedance of 50 Ω.

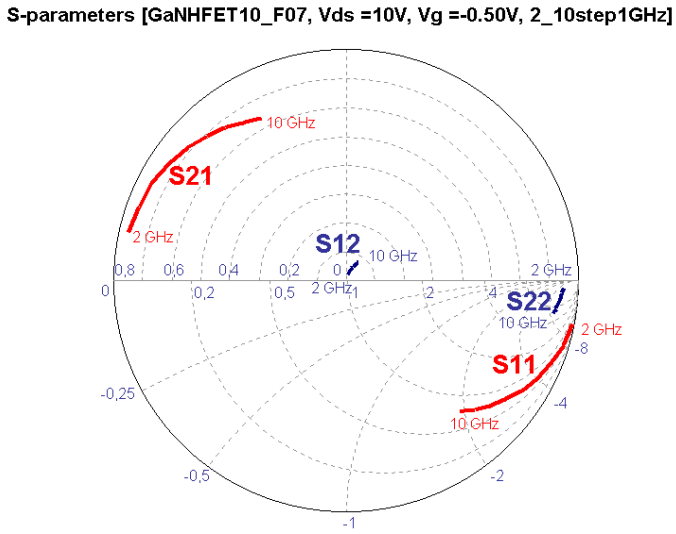


Fig. 3.4: S-parameters of a GaN HFET versus frequency at a certain bias condition. Typically the S21 is smaller than unity at a reference impedance of 50 Ohms.

Over all analyzed samples the minimum noise figure F_{min}, which describes the noise level of the transistor in the microwave region, varied between 0.54 to 10 dB at 2 GHz at an optimum bias condition in the saturation region of the transistor.

The frequency dependence of the minimum noise figure F_{min} and the associated gain G_a at room temperature from 2 GHz to 26 GHz is shown in *Fig. 3.5*. For increasing frequencies, F_{min} quickly increases and G_a decreases. To compare this result to the state-of-the-art technology, the lowest noise level of commercial GaAs transistors is also plotted to the chart. The comparison indicates that the noise performance of GaN HFETs still has to be improved to compete with GaAs.

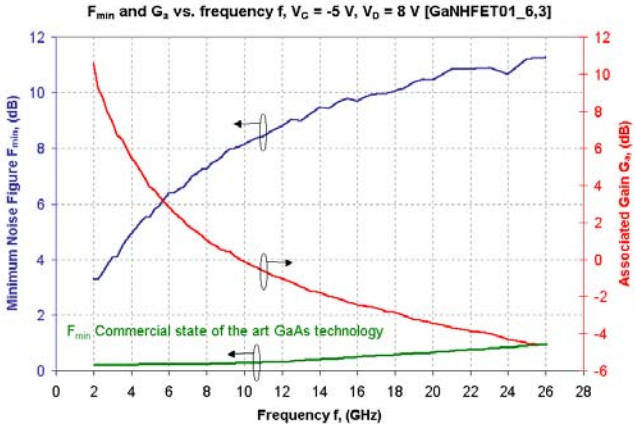


Fig. 3.5: Frequency dependence of the minimum noise figure and the associated gain of GaN HFETs at room temperature.

The bias dependence of two noise parameters can be seen in *Fig. 3.6*. In the x-y plane the known output characteristic like in *Fig. 3.3* is plotted. On the z-axis the minimum noise figure F_{min} (*Fig. 3.6a*) and the normalized equivalent noise resistance r_n (*Fig. 3.6b*) at 2 GHz are drawn for different bias conditions.

a) b)

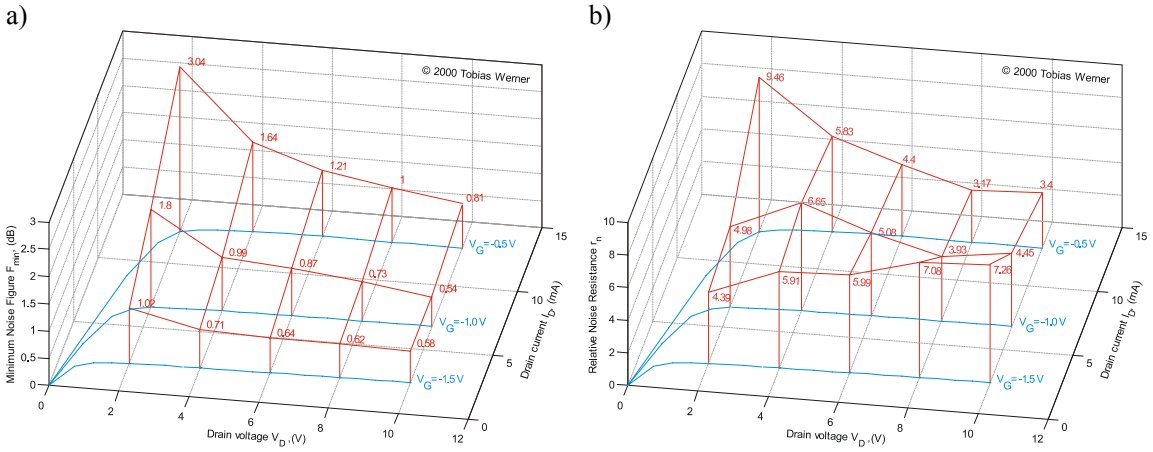


Fig. 3.6: Bias dependence of (a) the minimum noise figure F_{min} and (b) the normalized equivalent noise resistance r_n of GaN HFETs.

As can be seen, F_{min} decreases for increasing drain source voltages and decreasing gate source voltages. The tendencies for V_G, approaching the pinch off voltage and V_D, approaching the drain source breakdown voltage is not shown in the picture. In the first case F_{min} increases sharply, after passing a minimum. In the second case also a minimum can be found and F_{min} than rises again slowly. The optimum bias condition for F_{min} was typically found at about a third of the saturated drain source current I_{DS_S} and about half of the drain source breakdown voltage V_{DS_B} or expressed as equations:

$$I_{D_{opt}} = 1/3 \cdot I_{DS_S} \text{ and} \tag{3.1}$$

$$V_{D_{opt}} = 1/2 \cdot V_{DS_B} . \tag{3.2}$$

The normalized equivalent noise resistance r_n was found to be the most sensitive parameter of the four noise parameters. It showed large variations when including or excluding impedance points from the least-mean-square algorithm. r_n showed no clear tendency dependent on the bias condition (*Fig. 3.6b*).

The bias dependence of two kinds of gains is shown in *Fig. 3.7*. The associated gain at minimum noise figure G_a or the maximum available gain G_{max} (or MAG) occurs, if the input of the device is noise or power matched, respectively.

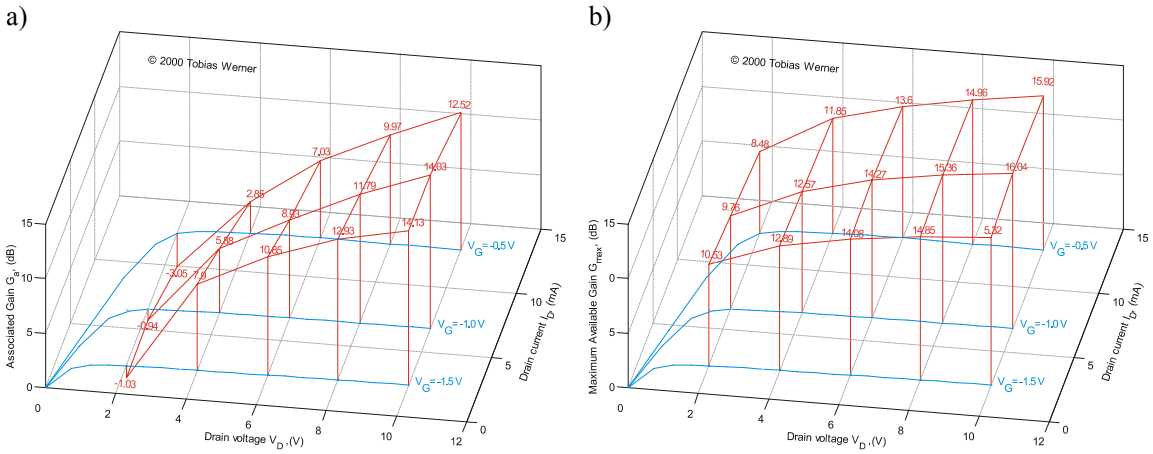


Fig. 3.7: Bias dependence of (a) the associated gain at minimum noise figure G_a and (b) the maximum available gain G_{max}.

G_a is always smaller as G_{max}. G_a decreases quickly for decreasing drain source voltages. The difference between G_a and G_{max} gets smaller and smaller as V_D increases. This means that the tradeoff between highest power and lowest noise gets more favorable as V_D increases. Comparing *Fig. 3.6a* and *Fig. 3.7a*, we can observe that the bias condition for a negligible deviation between G_a and G_{max} and the optimum F_{min} coincide at the same bias condition. This is important for low noise applications in first stage amplifiers since not only lowest noise but also highest gain matters as we can see from the Friis's cascade equation [20]

$$F = F_1 - \frac{F_2 - 1}{G_1}, \tag{3.3}$$

with F_i, the noise figure of the *i*-th stage, G_i, the gain of the *i*-th stage, and F, the overall noise figure.

The noise level of the flicker or 1/f-noise in the linear region of a transistor can be conveniently described by two parameters, the relative spectral current noise density S_I / I^2 and the Hooge parameter α_H, which varied between –132 to –109 dB/Hz and 7E-4 to 1E-1 at 100 Hz, respectively over all devices.

The flicker noise versus frequency in the linear region, expressed by the relative spectral current noise density S_I / I^2, is shown in *Fig. 3.8*. The slope of the curve varied between 0.9 and 1.4 as described in literature [23] but was typically close to unity.

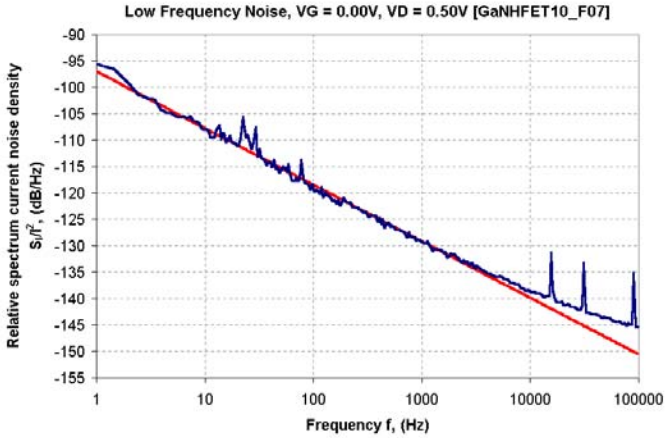


Fig. 3.8: Typical low frequency noise of a GaN HFET biased in the linear region. The slope of the red line is ideally proportional to 1/f.

The pure flicker noise was often superimposed by generation recombination noise, which leads to deviations from a straight line for higher frequencies. The spikes are due to disturbances from the power system frequencies (60 Hz) and frequencies at 15 kHz of unknown origin and their harmonics. The minimum Hooge parameter α_H was found to be as low as $7 \cdot 10^{-4}$ at zero gate bias and a drain source voltage of 0.5 V, what is comparable to results reported in [12].

4 MEASUREMENT SETUP

To characterize noise of transistors, specific setups with various instruments have to be used. The low frequency noise has to be measured with a different system as the microwave noise. In the succeeding chapters we will discuss what instruments were used for the measurements and how they were assembled with each other for both systems, the low frequency noise and the microwave noise setup.

4.1 Microwave noise setup

A picture of the microwave setup is shown in *Fig. 4.1*.

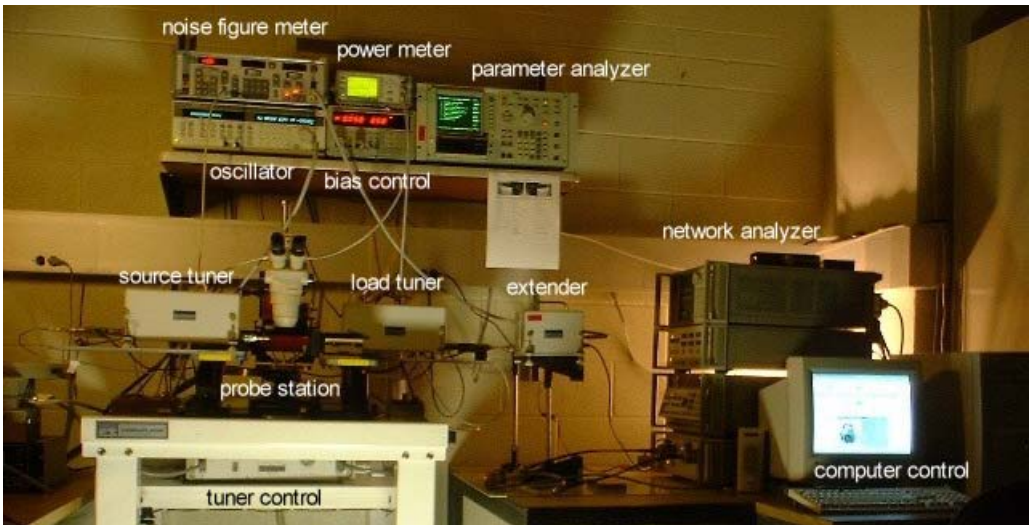


Fig. 4.1: The microwave setup to characterize DC-characteristics, S-parameters, noise and power of transistors in the microwave frequency range.

The instruments of the microwave setup were already available, but it was necessary to assemble and calibrate the system. Design decisions concerning the connections had to be made and several problems to calibrate the system had to be solved. Most important is, to make the system insertable (compare *Appendix F: Fixture Characterization*), what helps to keep the calibration process simple. This is not always possible and techniques like *Adapter-Removal* have to be used.

If even this method cannot be applied custom solutions have to be developed. For this purpose a program was written in *Matlab* (*Appendix F: Fixture Characterization*), which calculates the S-parameters of probe tips connected to a fixture from two sets of HP8510C error coefficients.

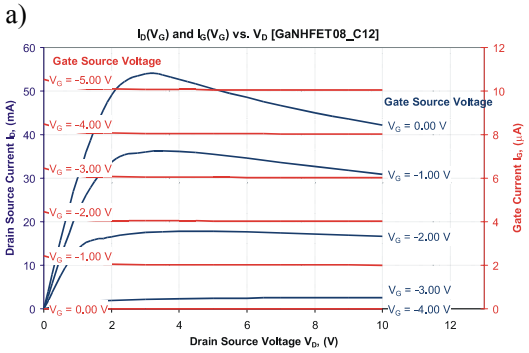
The latest version of the system uses microwave switches to select different setup configurations and is described in *Appendix G: Microwave Switch Control*.

With the system power, S-parameters and noise in a frequency range from 2 GHz to 12.4[2] GHz and DC-characteristics can be measured. For the topic of this work all measurement types, except power were relevant and the different setups and configurations of the instruments will be presented. The usual measurement sequence to examine the microwave noise of a transistor is the following:

- **DC-measurement** (*Fig. 4.2a*) at the beginning, to get a general idea about the maximum bias ranges of the device under test (DUT).
- **S-parameter measurements** (*Fig. 4.4a*) at the frequencies of interest for different bias conditions within the limits for the gate and drain voltage, determined by the DC-measurement.
- **Noise measurements** (*Fig. 4.11*) for the same conditions, concerning frequency and bias range, as used for the S-parameter measurements.

The DC-characteristics can be measured with the program *Automated IV-Curve Measurement* (*Fig. 4.14*), which controls the HP4145A parameter analyzer via the GPIB, at any time independent of the setup configuration.

a)



b)

Fig. 4.2: (a) Typical DC measurement result obtained with the aid of a (b) parameter analyzer (Hewlett Packard HP4145)

For S-parameters and noise measurements different instruments are used and assembled in a different way. These setups will be explained in the next two chapters.

[2] The system is actually designed for a frequency range of 2 GHz to 18 GHz, but is limited by the two bias-Ts at the input and output of the system that are only specified up to 12.4 GHz. All other components meet the requirements of 18 GHz as an upper frequency limit.

4.1.1 S-parameter configuration

The configuration of the system for S-parameter measurement is shown in *Fig. 4.3*.

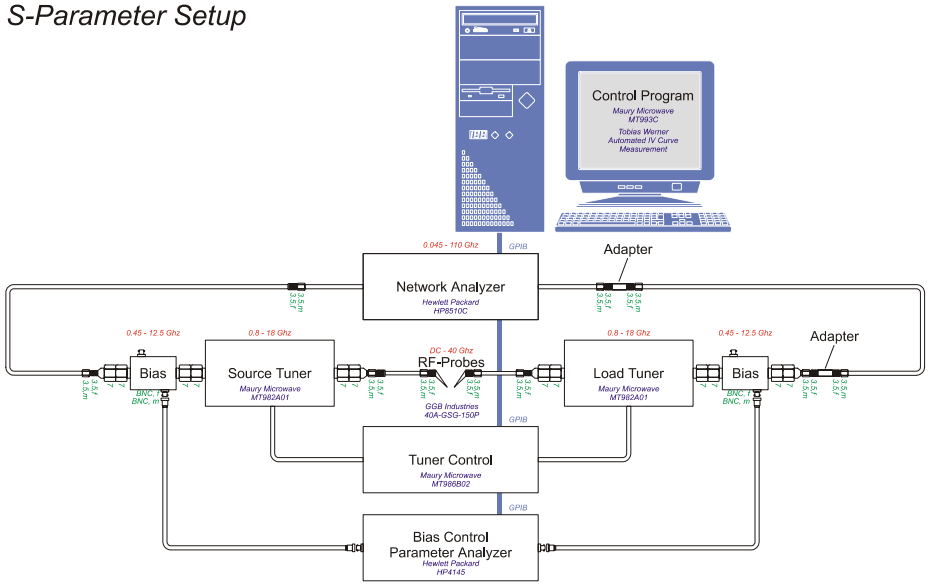


Fig. 4.3: The microwave setup configured for S-parameter measurements.

The Automated Tuner System (ATS) **software** MT993C from *Maury Microwave*[3] controls the entire setup via the General Purpose Instrument Bus (GPIB). For S-parameter measurements the **vector network analyzer** (VNA) HP8510C from *Hewlett Packard*[4] (*Fig. 4.4b*) is used. Its input and output ports are connected to **bias-Ts** HP11590B of *Hewlett Packard*, which are used to apply the gate and drain voltage provided by a **parameter analyzer** HP4145 of *Hewlett Packard* (*Fig. 4.2a*). The bias-Ts are necessary to adjust the working point of the analyzed transistor and to prevent interference with the measurement signal of the VNA.

[3] Maury Microwave, 2900 Inland Empire Boulevard, Ontario, California 91764, USA, Phone: +1(909) 987-4715, Fax: +1(909) 987-1112, www.maurymw.com

[4] Hewlett Packard (Agilent), www.agilent.com

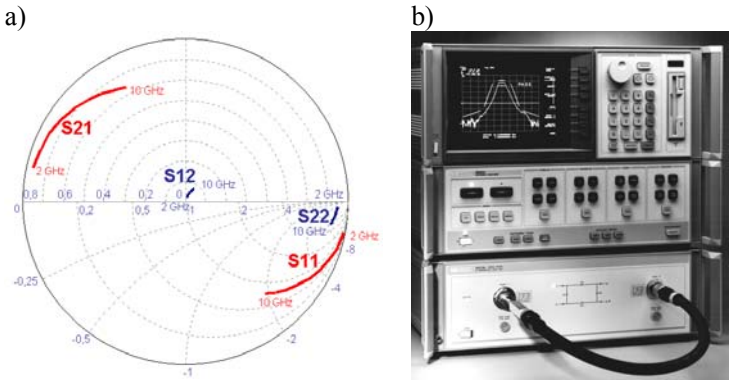


Fig. 4.4: (a) Typical result of a S-parameter measurement obtained with the aid of a (b) vector network analyzer (Hewlett Packard HP8150C).

A **tuner controller** MT966B02 from *Maury Microwave* manages two **mechanical tuners** MT982A01 (*Fig. 4.5*) from the same company at the source and load position. Tuners are used to change the impedance, seen by the DUT at its input and output and are set to 50 Ohms during the S-parameter measurement.

Fig. 4.5: Picture of two mechanical tuners (MT982A01) with a tuner controller (MT966B02) of Maury Microwave.

Two very-high-temperature **probes** VHT40A-GSG-150P (*Fig. 4.6a*) of *GGB Industries*[5], with ground-signal-ground configuration and 150 µm contact spacing, are used to contact transistors on-waver.

[5] GGB Industries, 4196 Corporate Square, Naples, FL 34104, USA, Phone: +1(941) 643-4400, Fax: +1(941) 643-4403, www.ggb.com

a) b)

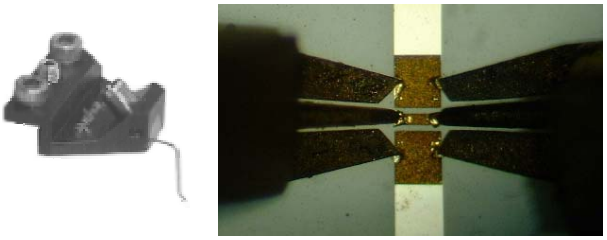


Fig. 4.6: (a) Probe tip (VHT40A-GSG-150P) and (b) probe tips contacting a through on a calibration substrate.

To get accurate results for the S-parameters, the VNA has to be calibrated before the measurement. This is required to shift the reference plane to the probe tips, where the measurement is carried out. Precisely known calibration standards (open, short, load, through) are measured and compared to the expected response. The VNA then calculates error coefficients, which compensate the loss, phase error and frequency response. The calibration can only remove *systematic* errors of the system. For the on-waver calibration, a **substrate** CS-5 from *GGB Industries* with a full-two-port-LRM[6] (line-reflect-match) technique was utilized. For the "reflect", the short standards were used. As recommended by a Maury engineer the averaging factor of the VNA was 128 for the reflect, match (50 Ohm load) and line (through standard) and 1024 for the isolation calibration with the load.

If S-parameter measurements of *active* devices are made, it is important to adjust the output power of the VNA to 0 dBm, because otherwise the device will be additionally biased by the VNA and not only by the bias control, as intended.

The S-parameter setup, like it is depicted in the Maury software can be seen in *Fig. 4.7*.

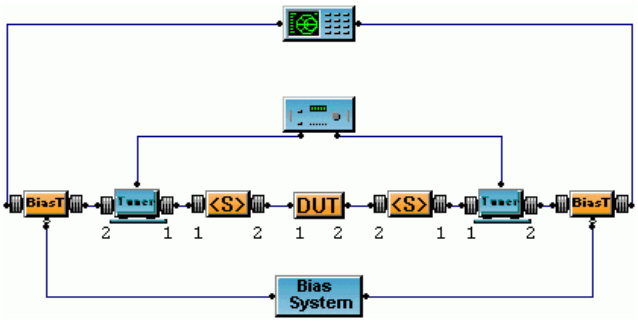


Fig. 4.7: The representation of the S-parameter setup in the ATS software of Maury Microwave.

[6] Also called TRM (Through-Reflect-Match)

4.1.2 Noise configuration

The core of the system, formed by the bias control, the bias-Ts, both tuners and the two probes, remains unchanged and is assembled like described in the previous chapter. A detailed view of the system, configured for noise measurement can be seen in *Fig. 4.8*.

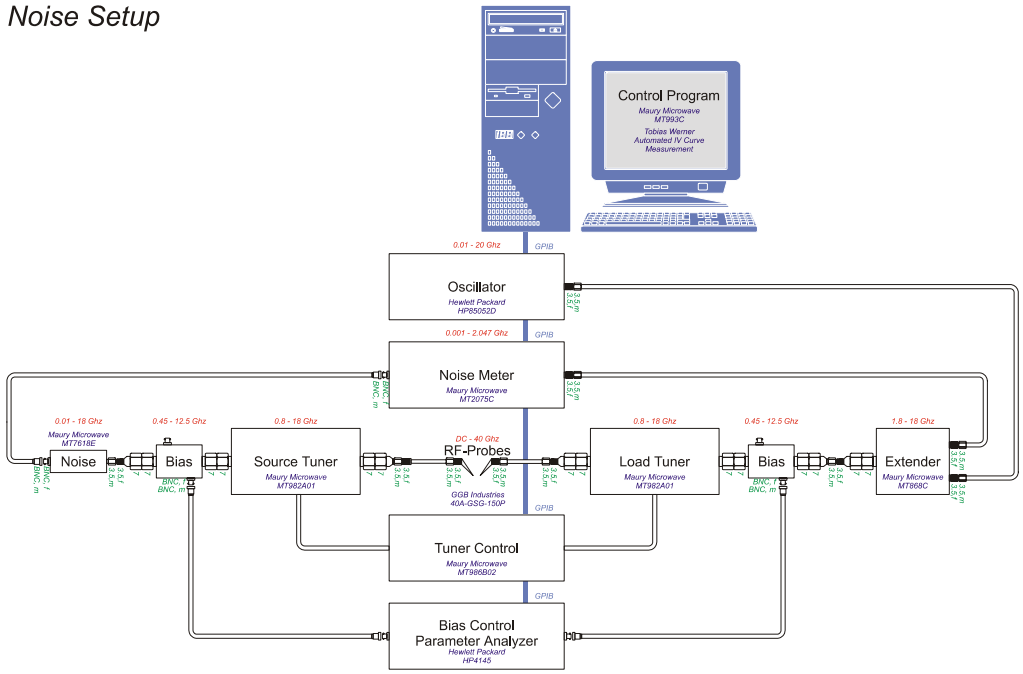


Fig. 4.8: The microwave setup configured for noise measurements.

At the input of the system a **noise source** MT7618E (*Fig. 4.9a*) from *Maury Microwave* is connected, which can be switched between two noise temperatures by a **noise figure meter** MT2075C (*Fig. 4.9b*) of *Maury Microwave*. The direct input tuning range of the noise figure meter is limited to frequencies below 2.047 GHz. The microwave setup however is designed to cover a frequency range up to 18 GHz, which is above the maximum direct input frequency of the noise figure meter. An external down-conversion to an intermediate frequency within the frequency range of the instrument is required [32].

a) b)

Fig. 4.9: (a) Noise source (MT7618E) and (b) Noise Gain Analyzer (MT2075C).

For this purpose a **frequency extender** MT868C of *Maury Microwave* is inserted at the output of the system. The noise signal is down-converted by a modulation with a signal, generated by an **oscillator** HP83752A of *Hewlett Packard*, to a frequency range, which is suitable for the noise figure meter.

For the noise measurement the **source** and **load tuner** have different responsibilities. The impedance setting of the load tuner has no influence on the noise level of the measurement, but it can be necessary to adjust its impedance to prevent the setup from oscillating. In some cases the system can be even more stable *without* a tuner at the load position [34]. To find the output impedance however at which the transistor is power matched, a load tuner must be present.

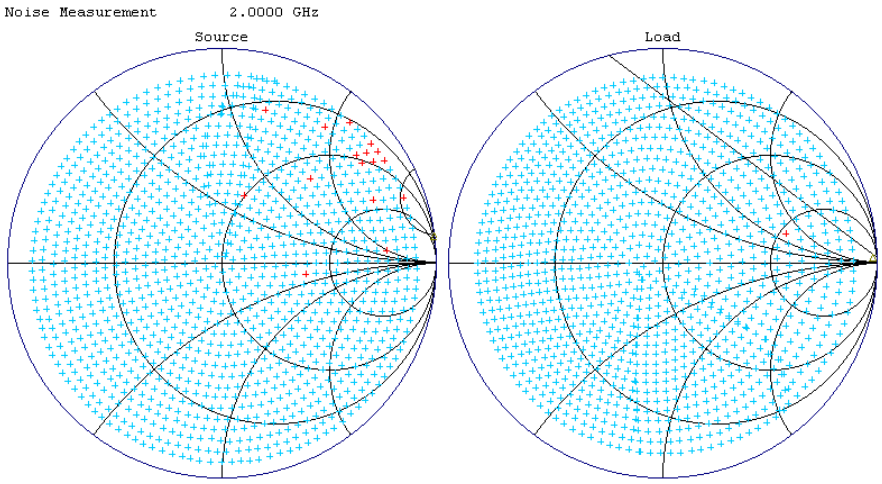


Fig. 4.10: Example of source and load positions for a noise measurement. The light blue crosses in the smith chart indicate the range, which can be covered by the mechanical tuners at 2 GHz. The red crosses in the source chart are the positions, where the noise figure is measured and will be used to determine the noise parameters. The red cross in the load chart point to the position of the load impedance.

The noise level of the DUT, expressed by the noise figure F, depends on the impedance at its input. The role of the **source tuner** is, to adjust this impedance level in order to find the position, where the lowest noise is exhibited by the DUT. *Fig. 4.10* shows a typical selection of source and load impedances for a noise measurement.

A typical noise measurement result obtained with the ATS is shown in *Fig. 4.11*.

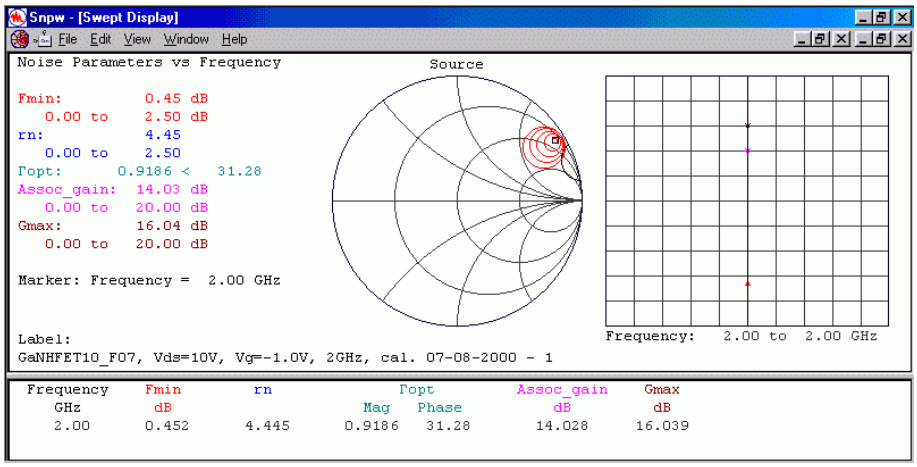

Snpw - [Swept Display]
File Edit View Window Help
Noise Parameters vs Frequency
Source
Fmin: 0.45 dB
0.00 to 2.50 dB
rn: 4.45
0.00 to 2.50
Γopt: 0.9186 < 31.28
Assoc_gain: 14.03 dB
0.00 to 20.00 dB
Gmax: 16.04 dB
0.00 to 20.00 dB
Marker: Frequency = 2.00 GHz
Frequency: 2.00 to 2.00 GHz
Label:
GaNHFET10_F07, Vds=10V, Vg=-1.0V, 2GHz, cal. 07-08-2000 - 1
Frequency Fmin rn Γopt Assoc_gain Gmax
GHz dB Mag Phase dB dB
2.00 0.452 4.445 0.9186 31.28 14.028 16.039

Fig. 4.11: Typical noise measurement screen in the ATS of Maury Microwave. The optimum source reflection coefficient Γ_{opt} is indicated by the square in the smith chart. Circles of constant noise figure for different source impedances are plotted in red color into the smith chart.

The noise setup, like it is depicted in the Maury software can be seen in *Fig. 4.12*.

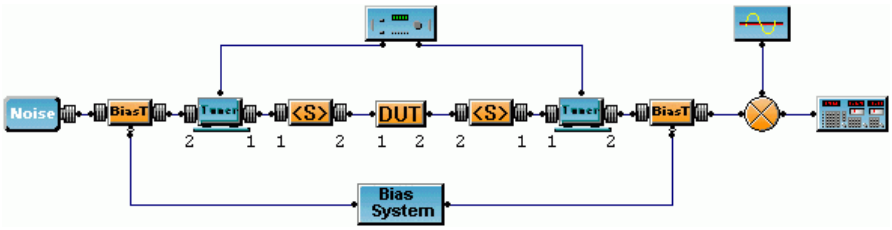


Fig. 4.12: The representation of the noise setup in the ATS software of Maury Microwave.

4.2 Low frequency noise setup

The low frequency noise setup is used to characterize the noise properties of transistors in a frequency range of typically 1 Hz to 100 kHz. The system is very sensitive to vibrations and electromagnetic disturbances and is therefore placed inside a shielded metal box on an air suspended table. In *Fig. 4.13* a picture of the employed instruments to measure the low frequency noise can be seen.

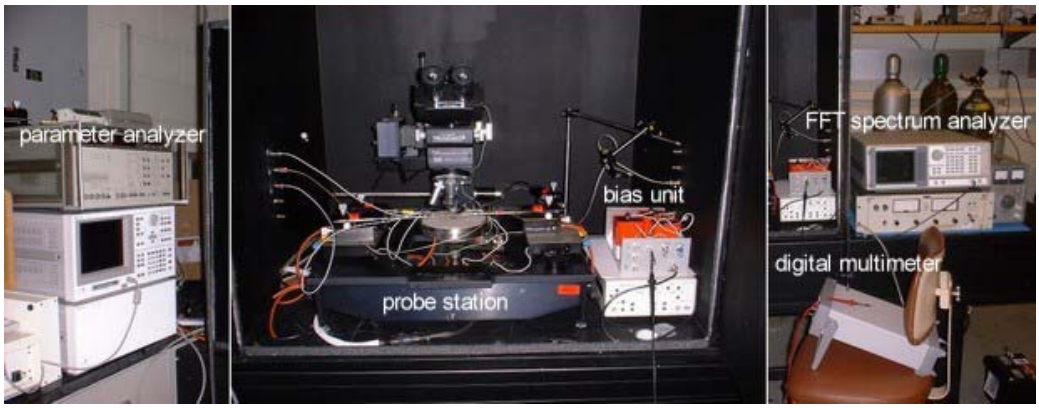


Fig. 4.13: Picture of the setup to measure the low frequency noise properties of transistors.

The output characteristic of the transistors was measured with the **parameter analyzer** HP4156B of *Hewlett Packard*. The measurement gives on the one hand an idea about the maximum bias ranges of the transistor and is on the other hand necessary, to extract the differential resistance of the transistor for a certain bias condition. The use of this resistance will be explained later.

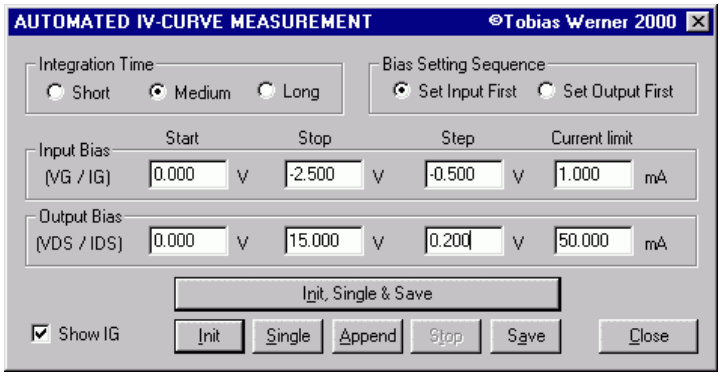
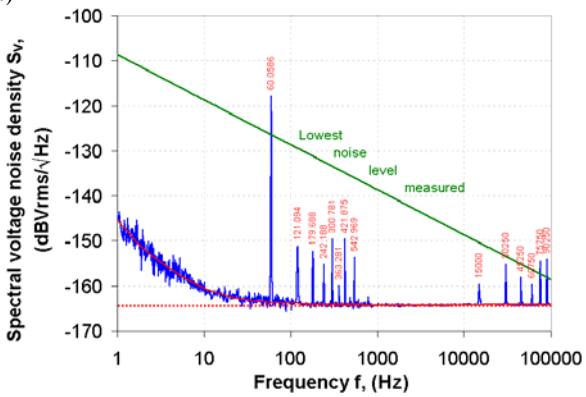


Fig. 4.14: User interface of the program Automated IV-Curve Measurement.

The parameter analyzer can be remoted over the GPIB by the program *Automated IV-Curve Measurement*, which is based on a driver from *Maury Microwave* and was extended in functionality. The interface of this program can be seen in *Fig. 4.14*.

The main instrument to measure the noise level of transistors is the SR770, a **FFT spectrum analyzer** (*Fig. 4.15b*), of *Stanford Research Systems*[7]. It measures the power spectral density (PSD) of a signal at its input at a resolution of 5 nVrms/Hz (-166dBVrms/Hz).

a)



b)

Fig. 4.15: (a) The noise floor of the low frequency noise measurement system. The spikes at harmonics of the power system frequency (60 Hz) cannot be suppressed by the shielding enclosure. The graph also shows disturbances at 15 kHz and harmonics of unknown origin. (b) The FFT spectrum analyzer (SR770) of Stanford Research Systems.

The measurement system's noise floor versus frequency is shown in *Fig. 4.15a* and is limited by the performance of the FFT spectrum analyzer. The lowest measured noise level was much higher than the noise floor and only some spikes, which can easily be separated from the noise contribution of the transistor, interfered with the measurement.

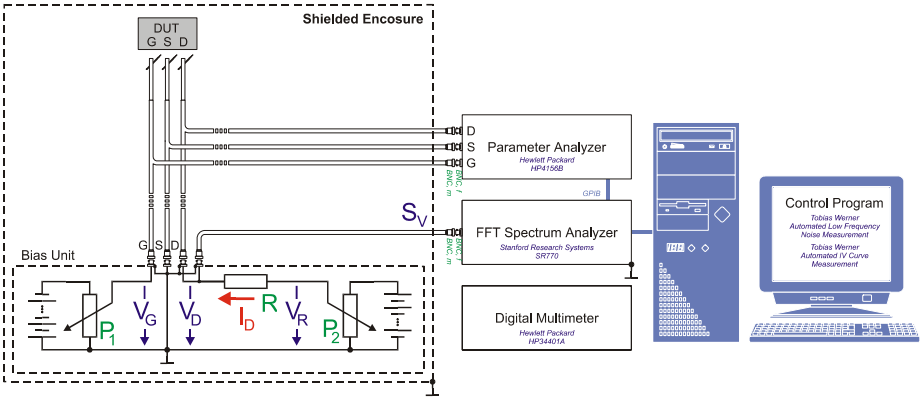


Fig. 4.16: Schematic view of the low frequency noise setup.

[7] Stanford Research Systems, 1290-D Reamwood Avenue, Sunnyvale, CA 94089, USA, Phone: +1(408)744-9040, Fax: +1(408)744-9049, www.stanfordresearch.com

As can be seen from the schematic view of the low frequency noise setup in *Fig. 4.16*, the input of the spectrum analyzer is connected to the drain of a biased transistor. The gate source voltage V_G and the drain source voltage V_D can be adjusted by potentiometers P_1 (100 Ω) and P_2 (2 KΩ), which are connected to batteries.

Batteries are used instead of power supplies, because the voltage is free from any *harmonic distortions*, caused by multiples of the fundamental power system frequency (60Hz), *spikes* and *electrical noise*, due to radio transmitters, power electronic circuits, arcing loads and switching power supplies.

To determine the drain source current I_D, a resistor R (100 Ω or 220 Ω) is placed between the potentiometer and the drain contact and I_D can be calculated by the expression

$$I_D = \frac{V_R - V_D}{R} . \tag{4.1}$$

All voltages were measured with a **digital multimeter** HP34401A from *Hewlett Packard*.

The quality of measurement relies to a great degree on the contact between the probe tips and the transistor pads. Therefore it is indispensable to clean the tips with alcohol proceeding to each measurement. The contact also depends on the applied pressure on the needles and should be varied until no significant alteration of the noise spectrum is noticed.

4.2.1 Measurement with the SR770

The power spectral density S_V of flicker noise is proportional to 1/f.

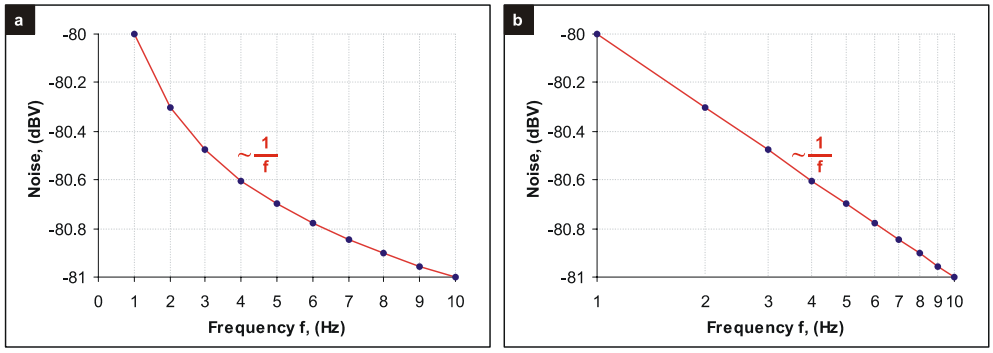


Fig. 4.17: Comparison between the same function, proportional to 1/f, plotted versus a linear (left) and a logarithmic (right) axis.

If S_V is plotted versus a logarithmic scale (*Fig. 4.17* b) instead of a linear (*Fig. 4.17* a) the dependence on 1/f is more perceptible, because the graph transforms into a straight line.

The logarithmic scale however interferes with the measurement procedure of the FFT spectrum analyzer. The SR770 divides the measurement range into 400 equidistant spaced steps and takes a measurement after each segment. For a measurement range from 1 Hz to 100000 Hz this means that every 250 Hz a measurement is taken.

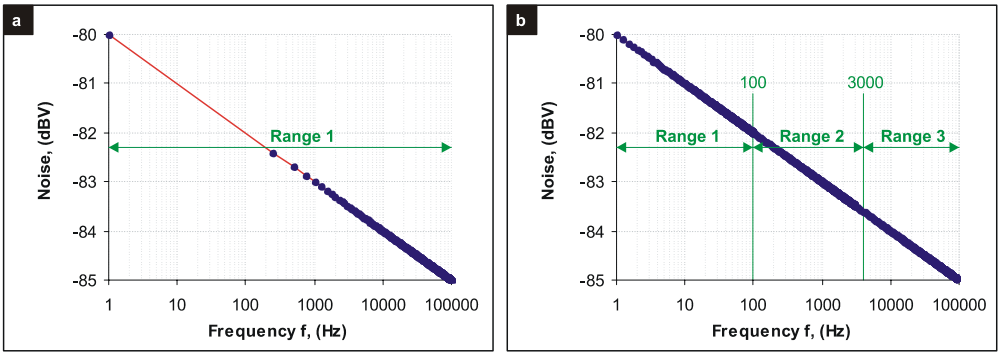


Fig. 4.18: The measurement has to be split into several measurement sections, because an insufficient number of samples represent the lower part of the spectrum.

Fig. 4.18 shows that in this case the lower part of the spectrum is only represented by two samples at 1 Hz and 251 Hz (*Fig. 4.18 a*). This is to imprecise and therefore the measurement range has to be composed by several individual measurement sections (*Fig. 4.18 b*).

For all low frequency noise measurements the frequency range was divided into three spans from 1 Hz to 100 Hz, from 100 Hz to 3000 Hz and from 3000 Hz to 100000 Hz. Because noise is a fluctuating quantity, a noise measurement consists of an averaged number of single measurements. *Table 4.1* shows, which number of averages was used for the measurement, depending on the frequency span.

Start frequency, (Hz)	Stop frequency, (Hz)	Number of averages
1	100	50
100	3000	200
3000	100000	500

Table 4.1: Number of averages for different frequency spans.

Although there is a possibility to store frequently used settings for a measurement in a file and to recall the settings later from disk, not all parameters are saved and have to be manually adjusted each time the frequency range is changed. This is a possible source of error, if the parameters are not carefully examined.

The conventional way to measure with the SR770, is the following:

- Recall a set of parameters for a certain measurement range from floppy disc and adjust parameters, which could not be recalled.
- Carry out the measurement.
- Save the results of the measurement on floppy disc.

This had to be repeated for every individual measurement section. Afterwards the measurements were combined by hand in Excel with overlapping sections in mind.

Because a large number of transistors had to be measured for an analysis of the correlation between the flicker and microwave noise, the decision was made to rather invest the time to create a program than to take the time to compile all separate measurements by hand.

This has several advantages:

- The measurement can run unattended and there is no need to interact, while the measurement is running. Other things can be done in the meantime.
- The data is directly transferred to the controlling computer. No floppy disc has to be used.
- The individual sections are combined automatically and the program eliminates overlapping sections. Combination errors of the numerous files are prevented.
- Eliminating unnecessary redundant samples and restricting the data to logarithmic equidistant steps can reduce the number of measurement points. Thus file size is decreased while the qualitative meaning is preserved.
- Wrong parameter settings and with it wrong measurement results can be prevented, because the program takes care of setting *all* parameters to the correct values.
- The measurement conditions and parameter settings are written directly into the file for further reference and no additional notes are needed. The measurement situation can therefore be reconstructed.
- The measurement file is named with the corresponding parameter settings and is not restricted to 8 characters. This helps to keep the work organized and to locate the files quicker.
- The measurement takes less time is more flexible.

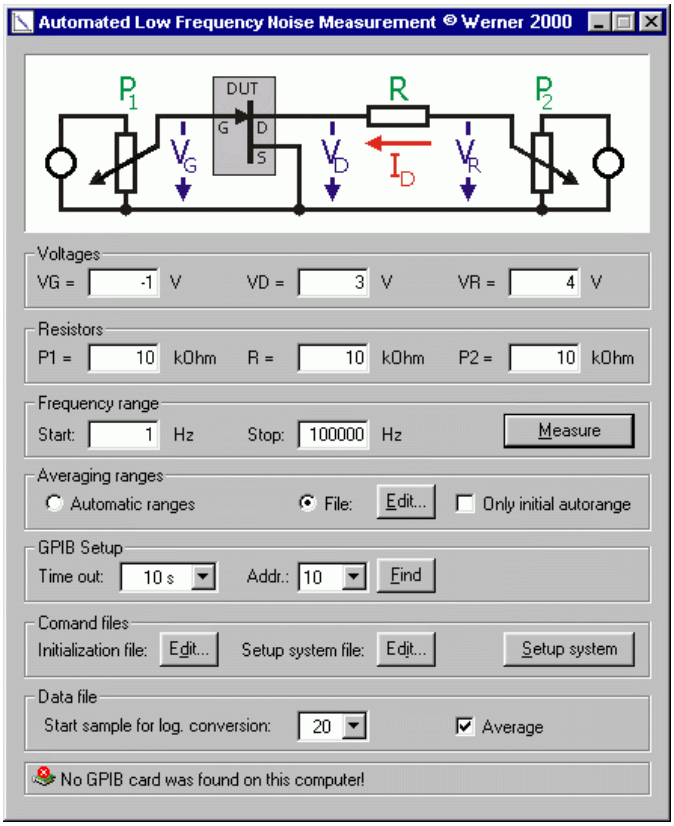


Fig. 4.19: The user interface of the program to measure the low frequency noise.

The program is named *Automated Low Frequency Noise Measurement (ALFNM)* and the user interface can be seen in *Fig. 4.19*. The description and manual of the program can be found in *Appendix E: Low Frequency Noise Measurement Program*.

To display the measurements, a macro was written in *Microsoft Excel*, which directly opens and displays the latest measurement result.

5 MEASUREMENT RESULTS

5.1 Flicker noise

To characterize the *low frequency noise*, the spectral voltage noise density S_V was measured at the drain of a biased transistor at room temperature.

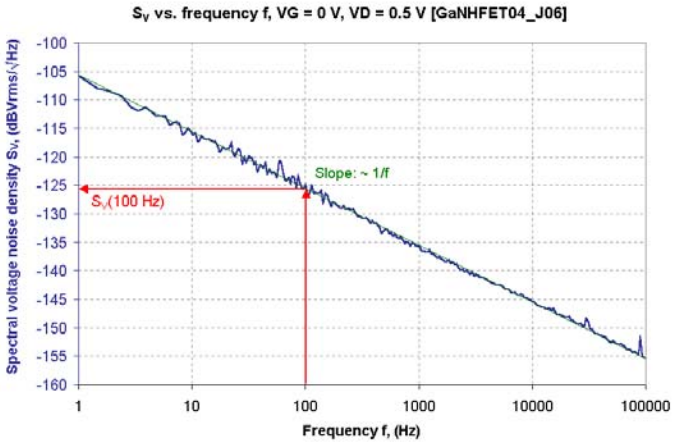


Fig. 5.1: Typical result of a low frequency noise measurement with the slope proportional to 1/f.

Fig. 5.1 shows a typical noise measurement result of S_V versus frequency from 1 Hz to 100 kHz for a transistor, biased at $V_G = 0$ V and $V_D = 0.5$ V (linear region). The noise spectrum in the presented example is ideally proportional to 1/f, but the slope showed a $1/f^{\gamma}$ dependence with γ varying from 0.9 to 1.4 over all measurements. The dominant source of noise in the low frequency range, the flicker noise, was sometimes overlaid by the so called *Generation Recombination Noise* for frequencies above 100 Hz (*Fig. 5.2*).

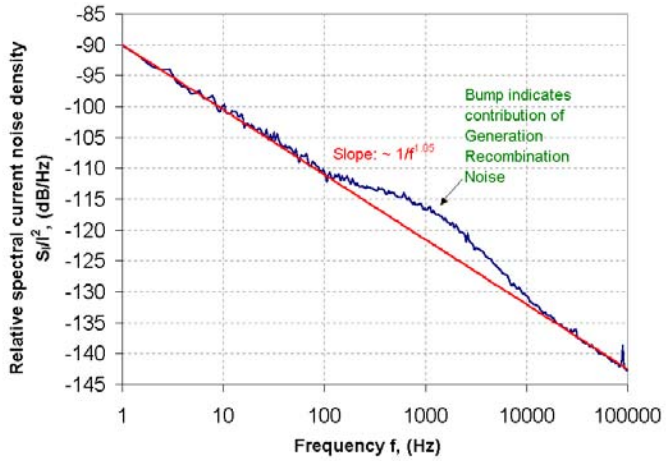


Fig. 5.2: Contribution of generation recombination noise.

To refer only to the flicker noise, the reference value of the spectral voltage noise density S_V was taken at 100 Hz to express the noise level of the low frequency flicker noise.

S_V is a function of the voltage, applied to the gate (V_G) and drain (V_D) of the transistor.

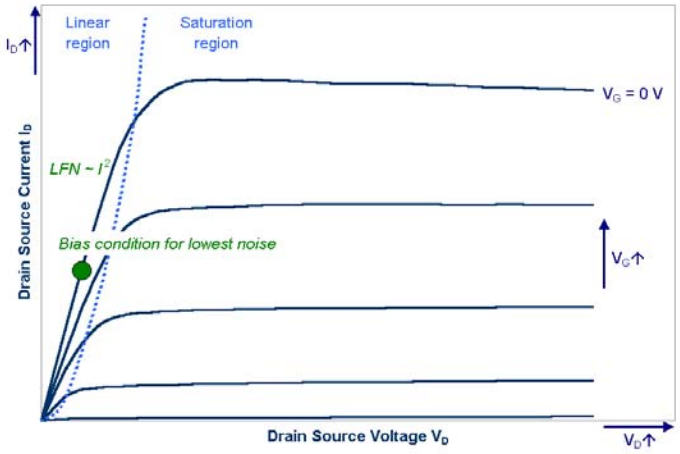


Fig. 5.3: Bias condition for lowest flicker noise.

In the linear region, the flicker noise is proportional to the squared drain current $I_D{}^2$ and is much smaller than in the saturation region of the transistor (*Fig. 5.3*).

Quantity to represent the flicker noise

The spectral voltage noise density S_V, measured at the drain of the transistor (Meas) depends on the following drain bias network, which can be represented like depicted in *Fig. 5.4*.

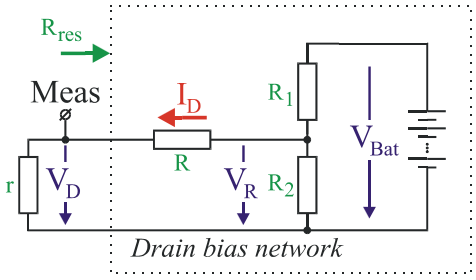


Fig. 5.4: Drain bias network.

The potentiometer (compare *Fig. 4.16*) to adjust the drain source voltage V_D can be described by two resistors R_1 and R_2. The differential resistance of the transistor depends on the drain voltage and is expressed by the resistor r. The resistor R is used to determine the drain current by measuring the two voltages V_D and V_R.

When adjusting S_V to the desired drain source voltage by changing the resistance ratio between R_1 and R_2, the bias network will change its resulting resistance R_{res}, seen by the DUT, which can be calculated by

$$R_{res} = R + \frac{R_1 \cdot R_2}{R_1 + R_2}. \tag{5.1}$$

The resistors R_1 and R_2 can not be measured in situ and were determined by measured voltages. The derivation of the formula relating the voltages with the resistors can be found in *Appendix B.2 Estimation of Rres for the present measurement system*.

The altered drain bias network also affects of course the measured spectral voltage noise density. To have a common base to compare measurement results independent of the bias network, the spectral current noise density S_I was calculated by

$$S_I = S_V \cdot \left(\frac{r + R_{res}}{r \cdot R_{res}} \right)^2, \tag{5.2}$$

where r is the differential resistance, and R_{res} the resulting bias network resistance. A detailed derivation of (5.2) can be found in *Appendix B.1 Derivation of the Equation relating SI with SV*.

The measured transistors on the wavers had the same gate length (0.25 µm) and gate width (100 µm), but different source drain spacings. To examine, if this influences significantly the result of the correlation between the flicker and the microwave noise, the Hooge parameter α_H, which takes into account this drain source spacing, was calculated.

To examine, if the correlation coefficient is varying considerably dependent on the applied parameter, the minimum noise figure F_{min} was not only compared to S_V, S_I and the Hooge parameter α_H, but also to the normalized spectral current noise density $S_I / {I_D}^2$ (in the following only referred to as S_I / I^2), which is often referred to in papers. It normalizes on the squared drain current, due to the fact that the flicker noise in the linear region of a transistor is proportional to ${I_D}^2$. Furthermore, the comparison between S_I , S_I / I^2 and α_H allows to separate the influence of the normalization to ${I_D}^2$ and the contribution of the different source drain spacings.

5.2 Microwave noise

To characterize the *microwave noise*, the minimum noise figure F_{min} was estimated at 2 GHz at room temperature with the help of the Automated Tuner System Software of *Maury Microwave*.

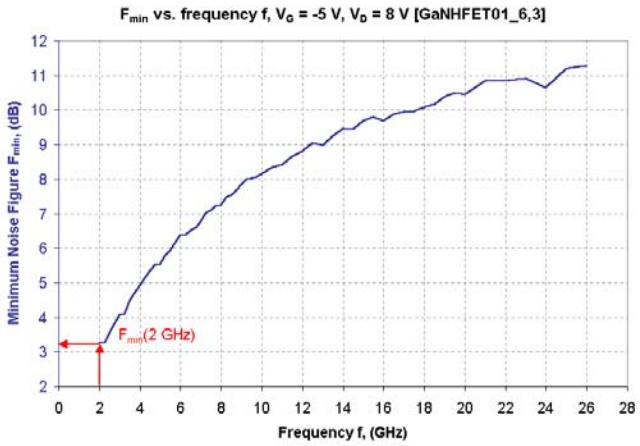


Fig. 5.5: Frequency dependence of the minimum noise figure F_{min}.

Fig. 5.5 shows a typical noise measurement result of F_{min} versus frequency from 2 GHz to 26 GHz for a transistor biased at V_G = -5 V and V_D = 8 V (saturation region). F_{min} is also a function of the voltage, applied to the gate (V_G) and drain (V_D) of the transistor.

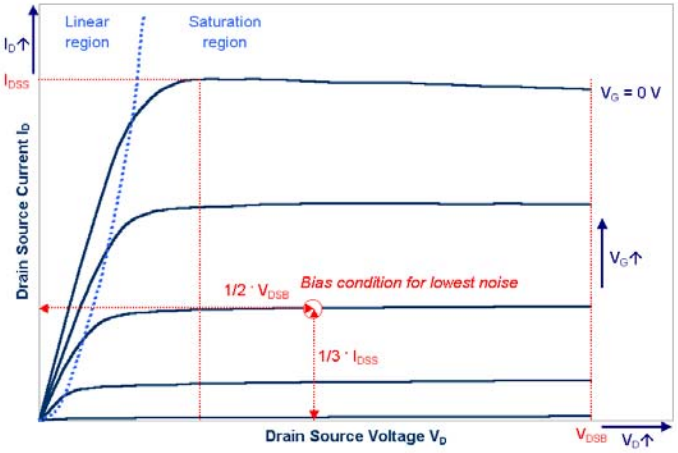


Fig. 5.6: Bias conditions for lowest microwave noise.

The minimum noise figure F_{min} of the examined GaN HFETs was found to be minimal for a bias condition of approximately a third of the saturated drain source current[8] I_{DS_S} and half of the drain source breakdown voltage V_{DS_B}, thus in the saturation region (*Fig. 5.6*).

5.3 Correlation between the flicker and the microwave noise

A graphical way of analyzing a dependence of two data ranges is, to plot them versus each other in a so-called scatter plot and to examine a visible tendency of the points in the graph.

If a dependence of two data ranges (in our case the parameter, representing the level of the flicker noise and the microwave noise) is not directly perceptible, a mathematical approach can help to identify the degree of reliance between the two ranges. The correlation coefficient is such a mathematical aid and a short overview is given in *Appendix C: Correlation*.

To investigate a possible correlation between the low frequency 1/f-noise and the microwave noise, three different approaches A, B, and C were chosen as illustrated in *Fig. 5.7*.

[8] This current occurs when the gate-to-source voltage V_G is held to zero and the drain-to-source voltage V_{DS} is set to a specified value (usually about 3 V).

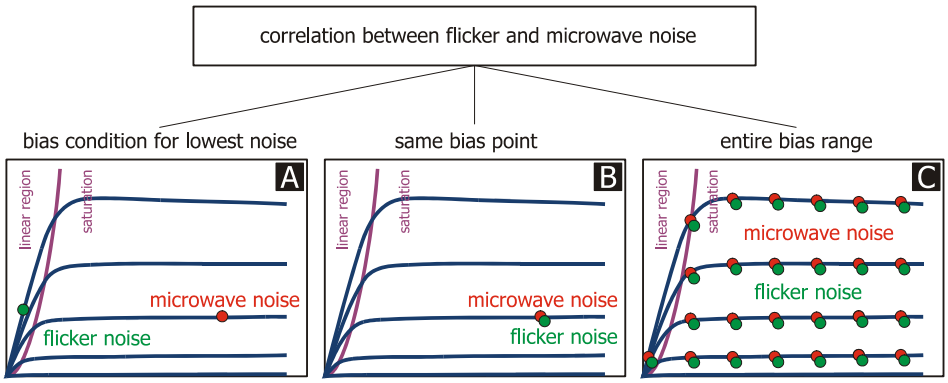


Fig. 5.7: Different approaches to analyze the correlation between the flicker and the microwave noise.

Method A compares the noise dependence at the bias condition for *lowest noise*. This means in the linear region for the low frequency noise and in saturation for the microwave noise (*Fig. 5.7A*).

Method B compares the flicker and the microwave noise for an *identical bias condition* in the saturation, what is the common working point for transistors (*Fig. 5.7B*).

Method C examines the dependence also for a *similar bias condition,* like in method B, but not only for one bias point and several transistors, but covering the *entire bias range* of *one* transistor (*Fig. 5.7C*).

5.4 Method A: Bias condition for lowest noise

Method A, bias condition for lowest noise, was carried out for 26 transistors on waver GaNHFET10, 15 transistors on GaNHFET08 and 18 transistors on GaNHFET04 as depicted in *Fig. 5.8*.

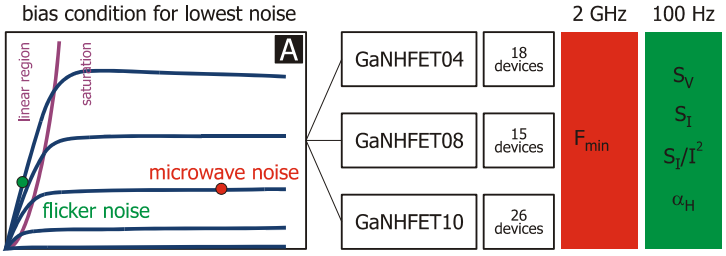


Fig. 5.8: Compared parameters and number of devices on wavers for method A.

5.4.1 Results for GaNHFET10

The minimum noise figure F_{min} was measured at 2 GHz in saturation at an optimum bias condition for lowest microwave noise and was compared to S_V, S_I, S_I / I^2 and α_H at 100 Hz in the linear region (V_G = 0 V, V_D = 0.5 V). To ensure reliable results and to better detect measurement errors, the microwave noise was measured at *four* different working points. Although the flicker noise measurement is sensitive to the contact quality between the probe tips and the transistor pads, the measurement process is less complex and one measurement is sufficient to ensure a consistent measurement result.

	1/f noise				microwave noise			
	VG = 0 V	VG = 0 V	VG = 0 V	VG = 0 V	VG = -1 V	VG = -1 V	VG = -1.5 V	VG = -1.5 V
	VD = 0.5 V	VD = 0.5 V	VD = 0.5 V	VD = 0.5 V	VD = 8 V	VD = 10 V	VD = 8 V	VD = 10 V
	S_V(100Hz)	S_I(100Hz)	S_I/I^2(100Hz)	Hooge(100Hz)	F_{min}(2GHz)	F_{min}(2GHz)	F_{min}(2GHz)	F_{min}(2GHz)
Device	dBVrms/√Hz	dBArms/√Hz	dB/Hz		dB	dB	dB	dB
B02	-130.21	-171.56	-122.90	1.54E-03	1.42	1.32	1.20	1.20
C01	-123.94	-163.62	-116.43	4.55E-03	1.08	1.05	0.76	0.77
D06	-126.56	-167.78	-119.37	2.31E-03	2.86	2.47	2.18	2.48
D07	-130.59	-172.38	-122.55	1.67E-03	1.51	1.43	1.55	1.46
E10	-123.57	-166.98	-116.33	6.99E-03	2.20	2.22	2.46	2.45
E12	-130.28	-173.23	-122.53	1.68E-03	2.84	2.40	2.13	1.84
E16	-125.47	-165.47	-118.43	2.87E-03	2.79	2.47	2.35	2.29
F07	-132.94	-175.38	-126.14	7.29E-04	0.73	0.54	0.62	0.58
F10	-124.17	-168.42	-115.77	7.94E-03	2.29	2.46	3.41	3.34
F16	-126.15	-166.40	-118.64	2.74E-03	1.56	1.30	1.65	1.65
F17	-127.28	-168.07	-119.50	3.37E-03	1.69	1.71	1.57	1.49
G01	-124.47	-165.85	-116.93	4.05E-03	1.25	1.28	1.27	1.04
G02	-129.94	-172.88	-123.23	1.43E-03	1.49	1.33	1.58	1.54
G05	-125.54	-168.74	-117.85	4.93E-03	2.33	2.27	2.95	2.86
G10	-126.65	-169.34	-118.50	4.24E-03	2.50	2.44	3.12	2.99
G11	-121.88	-163.75	-113.63	8.68E-03	1.29	1.03	0.94	0.86
G13	-118.37	-156.47	-111.43	1.44E-02	1.02	0.96	0.79	0.80
G14	-124.46	-166.03	-116.88	4.10E-03	1.42	1.38	1.46	1.44
G17	-125.90	-166.77	-118.78	3.98E-03	1.94	1.76	1.55	1.48
G20	-124.56	-166.82	-116.55	6.64E-03	2.41	2.20	1.84	1.71
H01	-123.32	-164.28	-116.18	4.82E-03	1.30	1.14	1.18	1.10
H11	-125.20	-164.81	-117.81	3.31E-03	1.06	0.84	0.79	0.77
H12	-126.33	-168.58	-118.24	4.50E-03	1.87	1.63	1.83	1.60
I05	-125.71	-168.20	-117.72	5.08E-03	1.88	1.85	2.49	2.40
I10	-125.57	-167.41	-117.76	5.03E-03	2.03	1.89	2.33	2.28
I17	-126.09	-166.07	-118.57	4.17E-03	1.70	1.50	1.20	1.10
max:	-118.37	-156.47	-111.43	1.44E-02	2.86	2.47	3.41	3.34
min:	-132.94	-175.38	-126.14	7.29E-04	0.73	0.54	0.62	0.58
average:	-125.97	-167.51	-118.41	4.45E-03	1.79	1.65	1.74	1.67
	-0.066	-0.207	-0.023	-0.094				
	-0.008	-0.185	0.044	-0.016				
	-0.013	-0.249	0.054	0.029				
	0.004	-0.222	0.062	0.031				
	correlation matrix							

Table 5.1: Correlation results for bias conditions of lowest noise; GaNHFET10.

Table 5.1 shows the individual low frequency and microwave noise results for each device on the waver GaNHFET10. The header row gives information about the measurement conditions, parameters and units. The lower main row shows the minimum, maximum and average values of the corresponding columns. The correlation coefficient was calculated for each column of the low frequency noise and the microwave noise and is shown in a matrix at the bottom of the table.

For the waver GaNHFET10, the correlation coefficient demonstrates only a negligible dependence on the microwave noise bias condition.

S_V represents the measured quantity, which is only specified for reference. S_I showed a negative correlation coefficient of about -0.2, what indicates no significant dependence considering the small number of available devices. A different correlation close to zero is obtained, if the spectral current noise density is normalized to the drain current (S_I / I^2) and additionally the source drain spacing is taken into account (α_H).

It is difficult to judge, which parameter is the most suitable to express the flicker noise level, however taking into consideration that for the microwave noise no normalization was applied, the *spectral current noise density* S_I appears to be the most expressive parameter. The scatter diagrams for S_I therefore are framed. To make it possible to draw own conclusions and to compare the parameters to each other, all parameters however were listed.

The following scatter diagrams will help to get a graphical idea of the dependence and to better judge the bare correlation result.

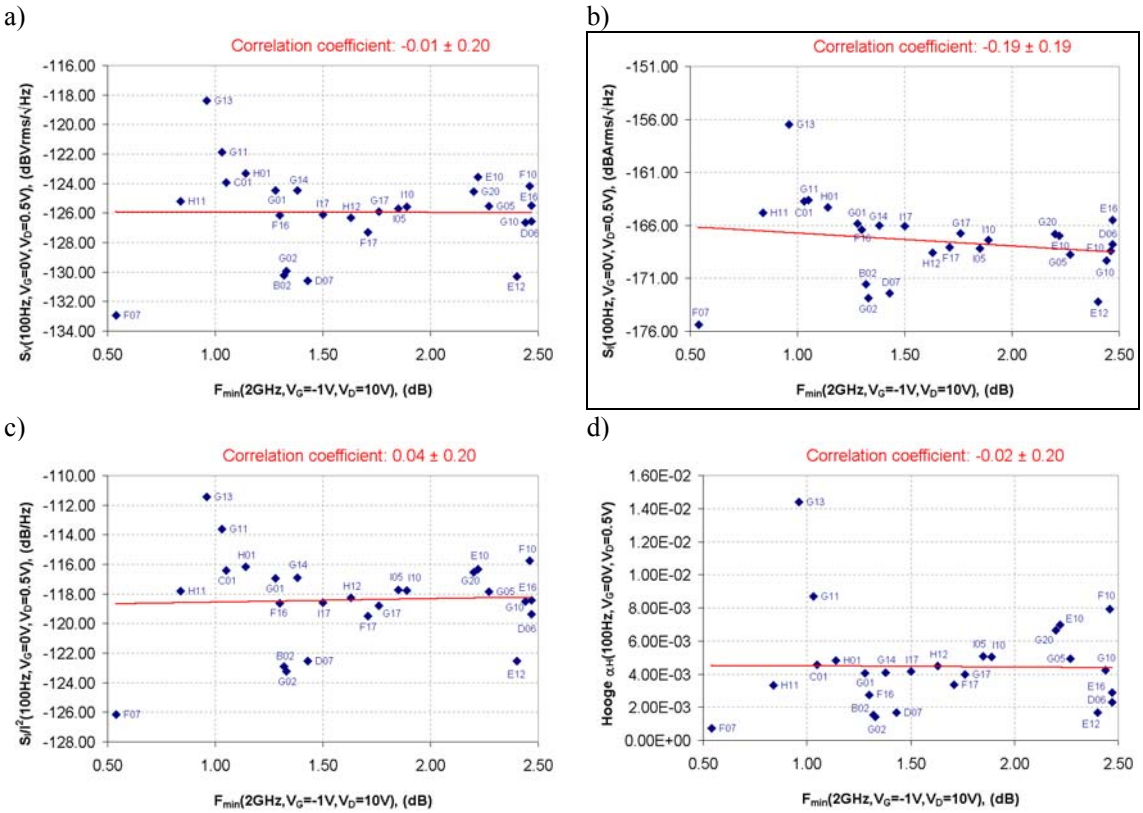


Fig. 5.9: Scatter diagrams for a comparison between F_{min} at 2 GHz, representing the microwave noise, and S_V, S_I, S_I/I^2 and α_H at 100 Hz, representing the flicker noise, GaNHFET10.

Fig. 5.9 shows four representative scatter diagrams for the bias condition with the lowest averaged minimum noise figure (1.65 dB). On the ordinate S_V, S_I, S_I / I^2 and α_H at 100 Hz are plotted versus the minimum noise figure F_{min} at 2 GHz on the abscissa. One dot in the diagram represents a certain transistor on the same waver with its minimum noise figure and corresponding low frequency noise parameter. The correlation coefficient and the regression line are drawn in red color to each plot. Also indicated with the correlation coefficient is the error due to a small number of observations, which is introduced in *Appendix C.5 Error due to small number of observations*. For all analyzed wavers the error was in the order of about ±0.2.

For a significant linear correlation the points in the diagrams should lie close to the regression line, what is not the case for this waver. The dots rather show a wide distributed pattern covering the entire plot area.

The normalization of S_I to the drain current leads to a slight displacement of the points (*Fig. 5.9b* versus *Fig. 5.9c*). This indicates that the correlation of α_H with F_{min} does not only reflect the influence of a different source drain spacing, but also the effect of the normalization to the drain current, which alters the correlation result.

The different point constellation between *Fig. 5.9c* and *Fig. 5.9d* is mainly due to the changed non-logarithmic scale, used for the Hooge parameter. A comparison, if also the Hooge parameter is displayed in dB is shown in *Fig. 5.10* and demonstrates a better agreement between the points. Still there is a deviation, what can be ascribed to the different source drain spacing of the transistors.

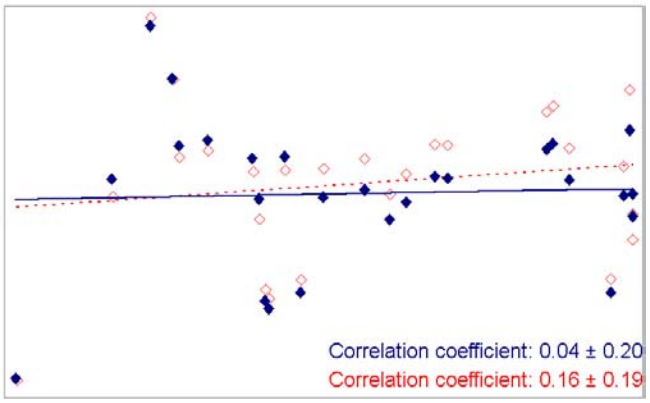


Fig. 5.10: Comparison between the point constellation of S_I/I^2 (filled dots, solid line) and the Hooge parameter in dB (non-filled dots, dashed line).

The highest value of the correlation coefficient results from the comparison between F_{min} and the spectral current noise density S_I, but a correlation coefficient of about -0.2 still does not indicate a significant dependence.

In summary it may be concluded for waver GaNHFET10, that the correlation coefficient is quite small and the points show no clear tendency. This indicates, that there appears to be no dependence between the low frequency noise and the microwave noise for this waver.

5.4.2 Results for GaNHFET08

The minimum noise figure F_{min} for this waver was measured at 2 GHz for *six* different bias points in the saturation region and was compared, as before, to S_V, S_I, S_I / I^2 and α_H at 100 Hz for one bias point in the linear region ($V_G = 0$ V, $V_D = 0.5$ V).

	1/f noise				microwave noise					
	VG = 0 V	VG = 0 V	VG = 0 V	VG = 0 V	VG = -1 V	VG = -1 V	VG = -1 V	VG = -2 V	VG = -2 V	VG = -2 V
	VD = 0.5 V	VD = 0.5 V	VD = 0.5 V	VD = 0.5 V	VD = 2 V	VD = 4 V	VD = 6 V	VD = 2 V	VD = 4 V	VD = 6 V
	S_V(100Hz)	S_I(100Hz)	S_I/I^2(100Hz)	Hooge(100Hz)	F_{min}(2GHz)	F_{min}(2GHz)	F_{min}(2GHz)	F_{min}(2GHz)	F_{min}(2GHz)	F_{min}(2GHz)
Device	dBVrms/√Hz	dBArms/√Hz	dB/Hz		dB	dB	dB	dB	dB	dB
A05	-126.87	-164.64	-120.16	2.89E-03	6.36	6.30	6.49	6.67	6.65	6.52
A12	-133.11	-170.01	-126.15	7.28E-04	2.68	2.10	2.23	1.63	1.66	1.75
A15	-131.01	-167.92	-123.67	1.29E-03	3.07	2.07	2.12	1.65	1.56	1.58
B01	-129.61	-166.38	-122.83	1.04E-03	4.10	3.38	3.43	2.55	2.43	2.45
B02	-129.68	-167.42	-122.64	1.63E-03	2.49	1.65	1.57	1.57	1.41	1.42
C12	-132.57	-167.11	-125.59	8.29E-04	2.30	1.71	1.85	1.21	1.20	1.24
C15	-131.51	-166.95	-124.68	1.02E-03	2.59	1.80	1.87	1.39	1.36	1.39
D05	-129.04	-164.90	-121.99	1.90E-03	3.05	2.04	2.07	1.51	1.47	1.47
D10	-129.10	-164.68	-122.17	1.82E-03	3.10	2.05	2.08	1.51	1.45	1.48
D17	-126.52	-161.47	-119.41	3.43E-03	5.44	4.41	4.25	5.16	4.96	4.40
F02	-129.08	-164.71	-121.63	2.06E-03	3.97	2.10	2.11	1.48	1.39	1.42
F20	-127.35	-162.93	-120.74	2.53E-03	2.40	1.93	1.99	1.43	1.38	1.41
J02	-125.00	-165.67	-117.65	5.15E-03	3.98	2.79	2.75	2.69	1.89	1.89
J05	-129.40	-165.09	-122.62	1.64E-03	2.68	2.05	2.08	1.56	1.59	1.62
L02	-128.27	-166.11	-121.30	2.23E-03	2.36	1.98	2.12	1.55	1.54	1.61
max:	-125.00	-161.47	-117.65	5.15E-03	2.30	1.65	1.57	1.21	1.20	1.24
min:	-133.11	-170.01	-126.15	7.28E-04	6.36	6.30	6.49	6.67	6.65	6.52
average:	-129.21	-165.73	-122.21	2.01E-03	3.37	2.56	2.60	2.24	2.13	2.11
	0.564	0.471	0.564	0.509						
	0.510	0.402	0.482	0.427						
	0.479	0.370	0.448	0.395						
	0.544	0.437	0.521	0.492						
	0.473	0.426	0.444	0.395						
	0.457	0.388	0.426	0.376						
	Correlation matrix									

Table 5.2: Correlation results for bias conditions of lowest noise; GaNHFET08.

Table 5.2 shows again the individual low frequency and microwave noise results for each device on the waver GaNHFET08.

Independent of the low frequency noise parameter, the correlation coefficient is increasing, if the bias condition of the microwave noise is chosen closer to that, where the low frequency noise was measured (*Fig. 5.11*).

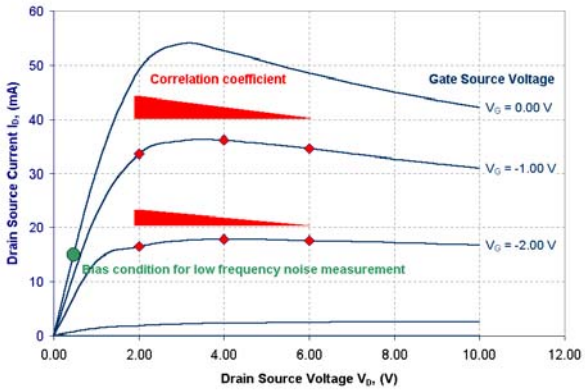

Correlation coefficient
Gate Source Voltage
V_G = 0.00 V
V_G = -1.00 V
V_G = -2.00 V
Bias condition for low frequency noise measurement
Drain Source Current I_D, (mA)
Drain Source Voltage V_D, (V)

Fig. 5.11: The correlation increases for decreasing source drain voltages.

This suggests, that a better correlation might be found, if the microwave and the low frequency noise are examined for an identical bias condition, what will be analyzed in *5.5 Method B: Same bias condition*.

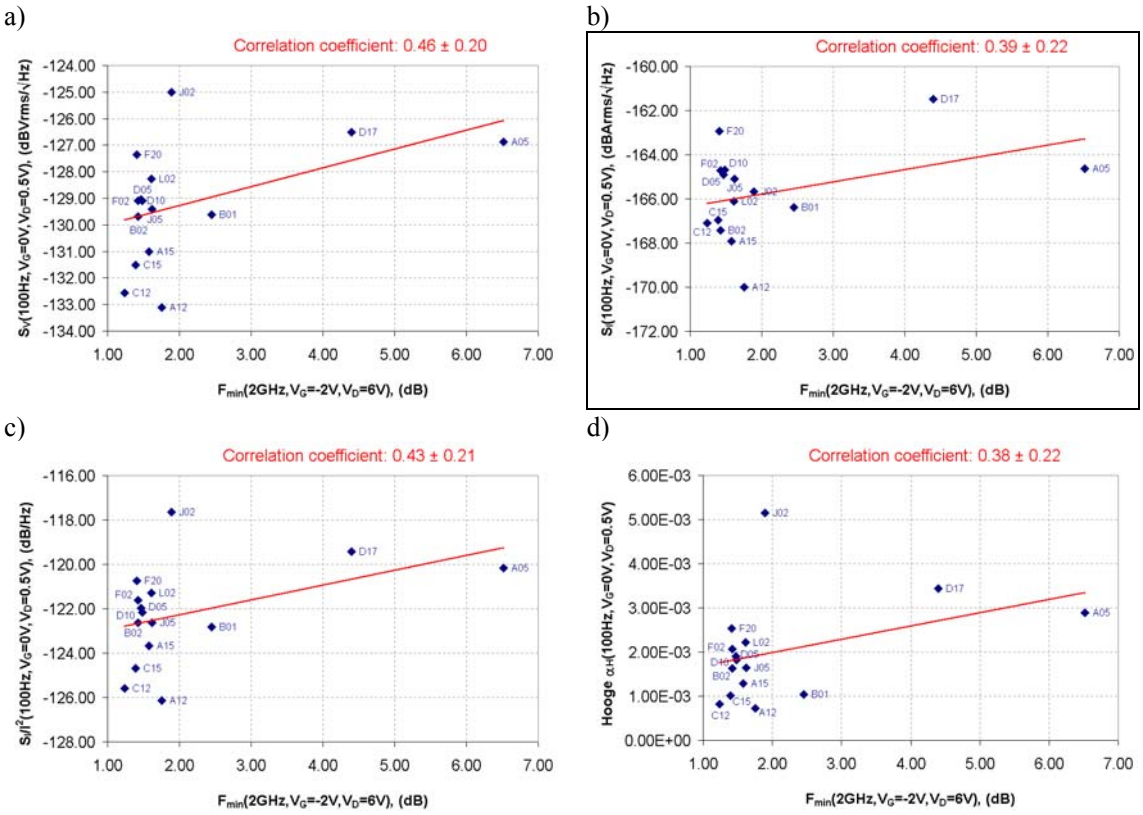


Fig. 5.12: Scatter diagrams for a comparison between the minimum noise figure F_{min} at 2 GHz, and S_V, S_I, S_I/I^2 and α_H at 100 Hz, GaNHFET08.

The four scatter diagrams in *Fig. 5.12* are arranged in the same way as described before for the bias condition with the lowest averaged minimum noise figure (2.11 dB).

The constellation of the points in *Fig. 5.12*, however, is very sensitive to errors, because only a few entries represent the microwave noise with elevated noise figures. To illustrate this sensitivity, the comparison in *Fig. 5.13* shows that the correlation coefficient changes considerably, if only one point is inserted into the data range.

a) b)

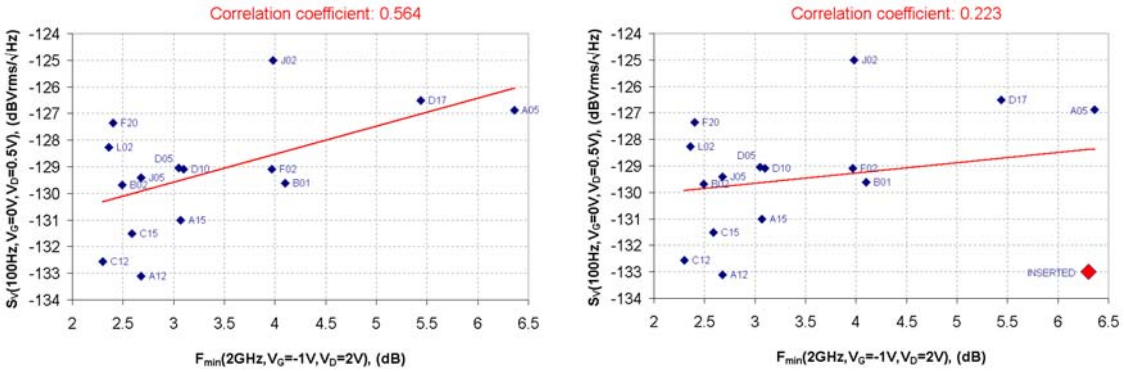


Fig. 5.13: Dependent on the constellation of the points in the scatter diagram, the correlation coefficient is very sensitive to errors. Only one additional point can change the correlation coefficient from 0.564 (a) to 0.223 (b).

Unfortunately, the analyzed devices were the only correctly working transistors on the waver GaNHFET08. Other transistors on the waver seemed to work, but could not be pinched off and were not considered for this examination.

The results for this waver could not be regarded as reliable due to the presented constellation sensitivity and the low number of analyzed devices. This example visualizes, that the bare correlation coefficient is only qualified expressive and that a look at the point constellation in a scatter diagram provides important information to judge the reliability of the correlation result.

5.4.3 Results for GaNHFET04

The minimum noise figure F_{min} for waver GaNHFET04 was measured at 2 GHz for *two* different bias points in the saturation region and was compared as before to S_V, S_I, S_I / I^2 and α_H at 100 Hz for one bias point in the linear region ($V_G = 0$ V, $V_D = 0.5$ V).

	1/f noise				microwave noise	
	VG = 0 V	VG = 0 V	VG = 0 V	VG = 0 V	VG = -0.5 V	VG = -0.5 V
	VD = 0.5 V	VD = 0.5 V	VD = 0.5 V	VD = 0.5 V	VD = 6 V	VD = 8 V
	S_V(100Hz)	S_I(100Hz)	S_I/I^2(100Hz)	Hooge(100Hz)	F_{min}(2GHz)	F_{min}(2GHz)
Device	dBVrms/√Hz	dBArms/√Hz	dB/Hz		dB	dB
E04	-128.29	-169.77	-120.82	1.66E-03	3.66	3.60
E05	-133.93	-178.00	-123.27	4.71E-03	3.00	3.04
E06	-139.50	-186.30	-131.57	1.39E-03	3.01	3.05
F03	-122.55	-165.53	-114.82	9.88E-03	3.95	4.08
F06	-135.76	-181.61	-122.51	1.12E-02	3.88	4.02
G04	-122.33	-168.09	-117.21	2.85E-02	3.26	3.22
G03	-128.95	-174.38	-109.46	1.70E-01	3.12	3.10
G08	-135.05	-180.84	-122.77	1.06E-02	4.74	4.77
H03	-130.63	-176.39	-117.65	2.58E-02	3.34	3.33
H05	-126.70	-169.90	-118.08	7.78E-03	2.92	2.86
H07	-133.11	-177.87	-123.17	4.82E-03	5.07	5.07
H08	-136.74	-182.64	-124.92	6.44E-03	5.62	5.63
I05	-126.78	-170.27	-119.51	3.36E-03	2.93	2.97
I06	-127.08	-169.89	-118.28	5.94E-03	5.58	5.62
J05	-127.12	-171.13	-118.33	7.34E-03	3.39	3.42
J06	-124.88	-169.46	-114.96	2.23E-02	3.69	3.68
J07	-121.12	-165.86	-110.62	8.66E-02	3.23	3.21
max:	-121.12	-165.53	-109.46	1.70E-01	5.62	5.63
min:	-139.50	-186.30	-131.57	1.39E-03	2.92	2.86
average:	-129.44	-173.99	-119.29	2.40E-02	3.79	3.80
	-0.272	-0.237	-0.235	-0.268		
	-0.284	-0.249	-0.246	-0.280		
	Correlation matrix					

Table 5.3: Correlation results for bias conditions of lowest noise; GaNHFET04.

Table 5.3 shows the individual low frequency and microwave noise results for each device on the waver GaNHFET04.

The correlation coefficient for this waver differs only slightly for the two microwave noise bias conditions.

Independent of the selected flicker noise parameter the correlation coefficient lies in the same range, what does not necessarily imply that the normalization to $I_D{}^2$ and the source drain spacing have no effect on the location of the points in the scatter diagram.

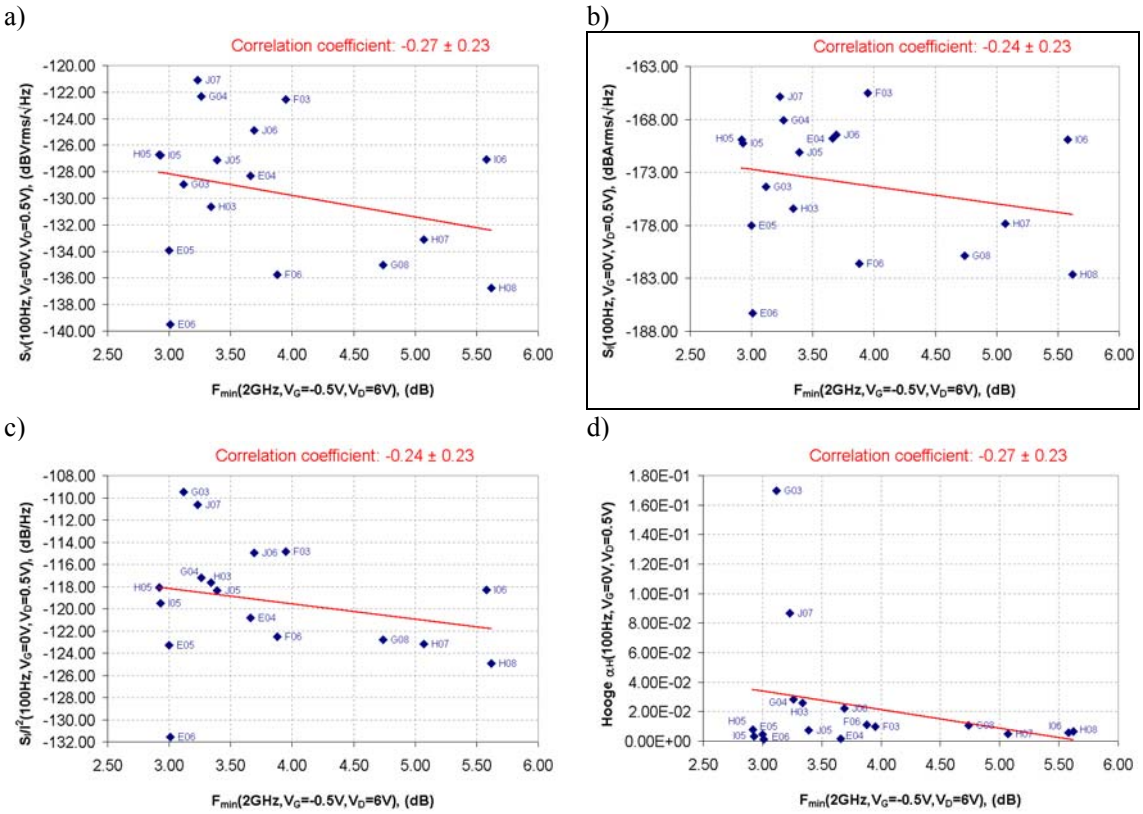


Fig. 5.14: Scatter diagrams for a comparison between the minimum noise figure F_{min} at 2 GHz, and S_V, S_I, S_I/I^2 and α_H at 100 Hz, GaNHFET04.

Fig. 5.14 shows again the four scatter diagrams for the bias condition with the lowest averaged minimum noise figure (3.79 dB) for waver GaNHFET04.

The correlation coefficient for all four low frequency noise parameters compared with the minimum noise figure resulted in a negative correlation between -0.24 and -0.27. Even so, the points are arbitrarily scattered and do not lie close to the regression line. An increased number of transistors on the waver GaNHFET04 would have been desirable, but only devices with widely differing properties were left on the waver and were not usable.

When comparing the correlation coefficient between F_{min} and the spectral current noise density S_I, obtained for GaNHFET04 and GaNHFET10, we can notice that both are negative and show about the same value of -0.2 ±0.2. No uniform correlation result is obtained, when other flicker noise parameters are taken to compare to F_{min}.

In all analyzed cases for method **A** the scatter diagrams showed a cloud of points that were widely scattered from the regression line. The correlation coefficient in general was small and no clear tendency for the dependence of the flicker and the microwave noise was found.

5.5 Method B: Same bias condition

This method was carried out for 21 devices on waver GaNHFET10, one of the wavers method A was already applied to. As for method A the minimum noise figure F_{min} at 2 GHz was compared to S_V, S_I, S_I / I^2 and α_H at 100 Hz, but this time for an *identical* bias condition in the saturation region of the transistor.

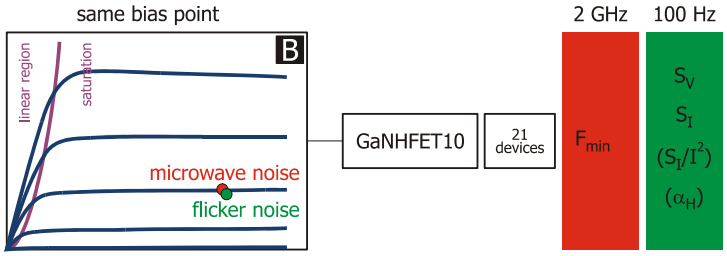


Fig. 5.15: Compared parameters and number of devices on waver GaNHFET10 for method B.

Dependent on the chosen bias conditions large variations in the correlation result were obtained. Therefore two cases, where only the gate source voltage V_G was altered, will be compared to each other.

5.5.1 Results for GaNHFET10, bias condition 1

The minimum noise figure F_{min} for waver GaNHFET10 was measured at 2 GHz for a working point in the saturation region (V_G = -1 V, V_D = 10 V) and was compared to S_V, S_I, S_I / I^2 and α_H at 100 Hz for the same bias condition.

	1/f noise				microwave noise
	VG = -1.0 V VD = 10 V S_V(100Hz)	VG = -1.0 V VD = 10 V S_I(100Hz)	VG = -1.0 V VD = 10 V S_I/I^2(100Hz)	VG = -1.0 V VD = 10 V Hooge(100Hz)	VG = -1.0 V VD = 10 V F_{min}(2GHz)
Device	dBVrms/√Hz	dBArms/√Hz	dB/Hz		dB
C01	-87.45	-137.54	-93.72	0.0464	1.05
D06	-87.73	-141.64	-86.80	0.1782	2.47
D07	-80.27	-133.12	-82.59	0.4949	1.43
E12	-95.21	-148.52	-96.32	0.0173	2.40
E16	-89.83	-141.77	-93.82	0.0378	2.47
F07	-98.87	-151.54	-101.53	0.0061	0.54
F10	-101.41	-155.25	-100.73	0.0056	2.46
F16	-91.74	-143.65	-95.79	0.0234	1.30
F17	-89.05	-141.04	-93.00	0.0447	1.71
G01	-91.62	-143.90	-95.06	0.0270	1.28
G02	-94.09	-146.90	-96.46	0.0184	1.33
G05	-94.51	-147.95	-95.22	0.0233	2.27
G10	-97.49	-150.74	-98.75	0.0121	2.44
G17	-91.35	-143.72	-94.62	0.0310	1.76
G20	-93.10	-144.76	-97.58	0.0195	2.20
H01	-91.76	-143.86	-95.49	0.0204	1.14
H11	-87.64	-137.77	-93.88	0.0406	0.84
H12	-95.05	-148.12	-96.78	0.0165	1.63
I05	-100.72	-154.08	-101.69	0.0051	1.85
I10	-94.47	-146.92	-97.58	0.0140	1.89
I17	-88.00	-138.08	-94.26	0.0443	1.50
max:	-80.27	-133.12	-82.59	0.4949	2.47
min:	-101.41	-155.25	-101.69	0.0051	0.54
average:	-92.44	-144.80	-95.32	0.0536	1.71
	-0.242	-0.324	-0.001	-0.038	
	correlation matrix				

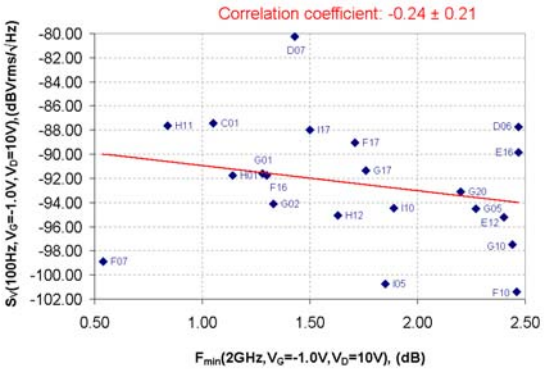
Table 5.4: Correlation results for an identical bias conditions in saturation; GaNHFET10.

Table 5.4 shows the individual low frequency and microwave noise results for each device on the waver GaNHFET10.

The correlation coefficient shows a large variation dependent on the applied flicker noise parameter, if either S_V, S_I or S_I / I^2 or α_H are used.

In saturation the flicker noise is no longer proportional to $I_D{}^2$ and the electron distribution in the channel gets inhomogeneous. Therefore the two flicker noise parameters S_I / I^2 and α_H have no significant meaning and are only presented in the table for completeness.

a)



b)

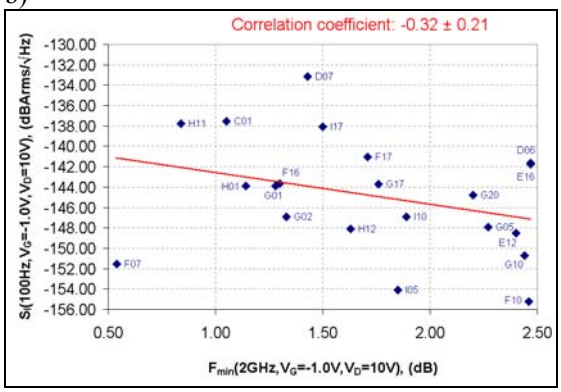


Fig. 5.16: Scatter diagrams for a comparison between the minimum noise figure F_{min} at 2 GHz, and S_V and S_I at 100 Hz.

Fig. 5.16 shows the scatter diagrams for a bias condition V_G = -1 V and V_D = 10 V of waver GaNHFET10. Only the graphs comparing S_V and S_I with F_{min} are of importance and show about the same point constellation. Comparing the flicker noise scales in *Fig. 5.9* and *Fig. 5.16* it can be noticed that the flicker noise level is much higher in saturation as in the linear region, as mentioned at the beginning of this chapter (*Fig. 5.5*).

Whereas the correlation coefficient of the same waver for method **A** was close to zero (-0.01 ±0.20) when correlating F_{min} and S_V, the regression line for this investigation, method **B**, shows a negative tendency and the correlation coefficient is -0.24 ±0.21.

The comparison between F_{min} and S_I resulted in both cases in a negative correlation coefficient of -0.19 ±0.19 for method **A** and of -0.32 ±0.21 for method **B**.

The points are, as before, randomly distributed and the correlation coefficient is still small enough to classify the result as uncorrelated.

5.5.2 Results for GaNHFET10, bias condition 2, worst case

The same examination was carried out for three additional bias conditions. The obtained results differ from the one before and the worst case will be presented in this section.

The noise level of transistors depend on a vast number of influences and the differing results show, how problematical it is, to find the right conditions for investigating the reliance between the flicker and the microwave noise.

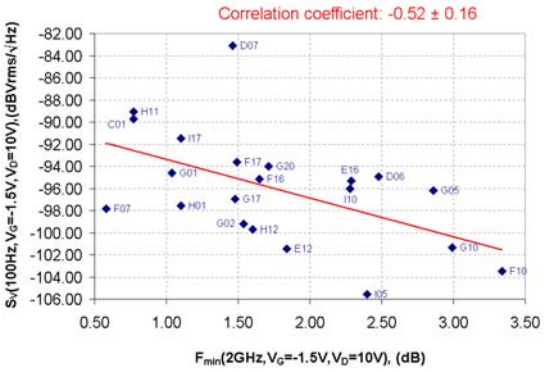
In this example all parameters were chosen as before, except the gate source voltage was decreased by 0.5 V from -1.0 V to -1.5 V.

	1/f noise				microwave noise
	VG = -1.5 V VD = 10 V	VG = -1.5 V VD = 10 V	VG = -1.5 V VD = 10 V	VG = -1.5 V VD = 10 V	VG = -1.5 V VD = 10 V
Device	S_V(100Hz) dBVrms/√Hz	S_I(100Hz) dBArms/√Hz	S_I/I^2(100Hz) dB/Hz	Hooge(100Hz)	F_{min}(2GHz) dB
C01	-89.74	-142.45	-92.36	0.0295	0.77
D06	-94.91	-149.81	-87.77	0.0489	2.48
D07	-83.08	-136.78	-82.93	0.1530	1.46
E12	-101.47	-156.42	-93.66	0.0089	1.84
E16	-95.31	-149.67	-92.23	0.0188	2.29
F07	-97.81	-152.53	-92.37	0.0163	0.58
F10	-103.48	-158.61	-93.53	0.0084	3.34
F16	-95.12	-149.52	-91.90	0.0191	1.65
F17	-93.62	-147.91	-91.02	0.0255	1.49
G01	-94.60	-149.07	-90.76	0.0237	1.04
G02	-99.18	-153.90	-93.66	0.0117	1.54
G05	-96.21	-151.20	-87.99	0.0369	2.86
G10	-101.35	-156.33	-93.34	0.0146	2.99
G17	-96.94	-151.51	-92.55	0.0163	1.48
G20	-94.00	-147.69	-93.91	0.0213	1.71
H01	-97.57	-152.19	-92.82	0.0141	1.10
H11	-89.09	-142.44	-90.04	0.0381	0.77
H12	-99.67	-154.55	-92.68	0.0128	1.60
I05	-105.58	-160.58	-97.40	0.0040	2.40
I10	-96.05	-150.69	-91.15	0.0191	2.28
I17	-91.46	-144.14	-94.14	0.0235	1.10
max:	-83.08	-136.78	-82.93	0.1530	3.34
min:	-105.58	-160.58	-97.40	0.0040	0.58
average:	-96.01	-150.38	-91.82	0.0269	1.75
	-0.523	-0.547	-0.049	-0.122	
	correlation matrix				

Table 5.5: Correlation results for an identical bias conditions in saturation; GaNHFET10.

Table 5.5 shows an increased correlation result for S_V and S_I. As before the other two flicker noise parameters have no meaning and are presented only for completeness.

a)



b)

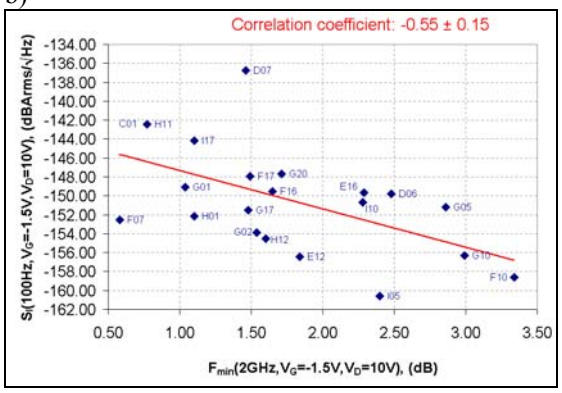
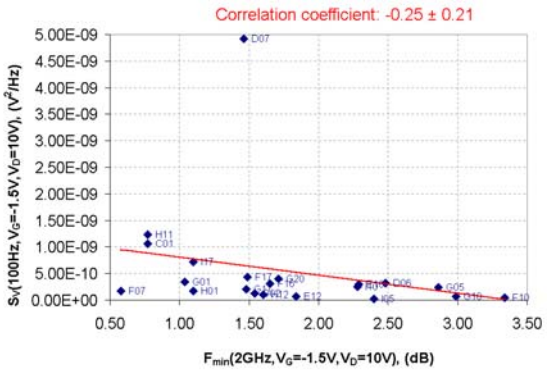


Fig. 5.17: Scatter diagrams for a comparison between F_{min} at 2 GHz, and S_V and S_I (logarithmic scale) at 100 Hz for a altered gate source voltage.

Fig. 5.17 shows again the two scatter diagrams, this time for the bias condition V_G = -1.5 V and V_D = 10 V of waver GaNHFET10. As can be seen from the two graphs, comparing S_V and S_I with F_{min}, the point constellation shows a clear negative tendency. This could indicate that there is a possible partly correlation between the flicker and the microwave noise and shows again the sensitivity of the analysis.

When using a non-logarithmic scale for the flicker noise parameters (dB is a logarithmic scale) the correlation coefficient decreases to -0.25 ±0.21 and -0.28 ±0.20 for S_V and S_I as parameters, respectively and is illustrated in *Fig. 5.18*.

a)



b)

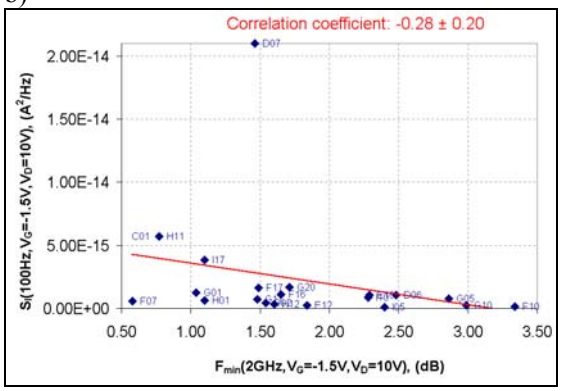


Fig. 5.18: Scatter diagrams for a comparison between F_{min} at 2 GHz, and S_V and S_I (non-logarithmic scale) at 100 Hz for an altered gate source voltage.

To consider all possible cases and to analyze the deviation of the correlation coefficient for different working points, would have required additional measurements.

5.6 Method C: Entire bias range

In contrast to the preceding methods, where numerous transistors on the same waver were examined, method C was carried out for 29 working points of a single transistor on waver GaNHFET01, as illustrated in *Fig. 5.19*. The minimum noise figure and the flicker noise parameter were estimated for an identical bias condition, covering the entire bias range of the analyzed transistor.

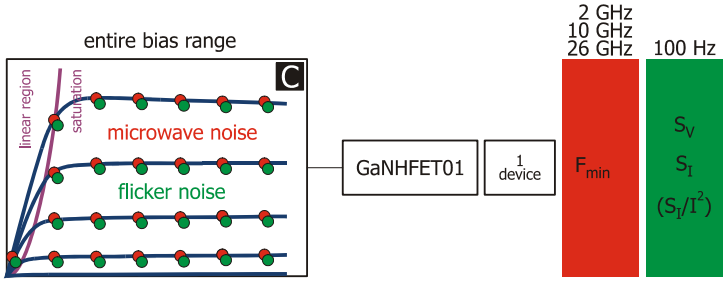


Fig. 5.19: Compared parameters and number of devices on wavers for method C.

5.6.1 Results for GaNHFET01

The minimum noise figure F_{min} was measured at 2 GHz , 10 GHz and 26 GHz and was compared to S_V , S_I , and S_I / I^2 at 100 Hz. As before, S_I / I^2 is only listed for reference and is no expressive parameter, because working points in the saturation region of the transistor are compared to each other.

bias voltage		1/f noise			microwave noise		
VG	VD	S_V(100Hz)	S_I(100Hz)	S_I/I^2(100Hz)	F_{min}(2GHz)	F_{min}(10GHz)	F_{min}(26GHz)
(V)	(V)	dBVrms/√Hz	dBArms/√Hz	dB/Hz	dB	dB	dB
-4.2	5	-95.20	-148.75	-95.37	2.89	7.63	10.53
-4.45	5	-96.44	-149.71	-93.00	2.99	7.71	10.61
-4.72	5	-98.44	-151.57	-92.48	2.95	7.78	10.63
-5.05	5	-96.73	-149.76	-88.38	3.12	7.83	10.51
-5.52	5	-98.61	-151.47	-84.69	3.53	7.62	9.67
-4.28	8	-99.28	-154.04	-80.07	2.74	7.77	11.45
-4.53	8	-99.49	-154.27	-81.87	2.98	7.84	11.45
-4.8	8	-99.13	-153.92	-82.86	2.98	7.98	11.39
-5.12	8	-98.56	-153.35	-81.98	3.28	8.14	11.27
-5.53	8	-100.32	-155.10	-83.06	3.48	8.23	10.79
-4.34	10	-98.86	-154.26	-84.63	2.80	7.77	11.74
-4.85	10	-97.53	-152.93	-82.47	3.11	8.03	11.80
-5.16	10	-97.18	-152.57	-82.40	3.00	8.18	11.77
-5.55	10	-98.08	-153.47	-82.10	3.20	8.37	11.32
-4.41	12	-97.21	-152.77	-86.02	2.79	7.86	12.09
-4.66	12	-97.74	-153.30	-85.56	2.82	7.93	12.02
-4.92	12	-96.56	-152.12	-82.49	3.07	8.05	12.01
-5.21	12	-94.99	-150.55	-81.43	3.17	8.23	11.96
-5.6	12	-95.05	-150.61	-80.71	3.00	8.46	11.61
-4.53	15	-97.10	-152.10	-86.42	2.68	7.90	12.16
-4.78	15	-96.31	-151.30	-86.42	2.80	8.02	12.10
-5.03	15	-97.28	-152.27	-86.76	3.04	8.15	12.21
-5.32	15	-96.09	-151.06	-87.71	3.37	8.40	12.21
-5.67	15	-97.99	-152.97	-88.96	3.60	8.64	11.82
-4.74	20	-99.60	-150.58	-91.87	2.95	8.01	12.37
-4.97	20	-100.36	-151.39	-91.81	3.00	8.08	12.33
-5.21	20	-99.19	-150.28	-89.65	3.04	8.19	12.34
-5.47	20	-97.75	-148.89	-87.28	3.48	8.44	12.45
-5.82	20	-100.08	-151.29	-88.19	3.04	8.71	12.01
max:		-94.99	-148.75	-80.07	3.60	8.71	12.45
min:		-100.36	-155.10	-95.37	2.68	7.62	9.67
average:		-97.83	-151.95	-86.09	3.07	8.07	11.61
		-0.085	0.058	0.069			
		-0.034	0.026	0.171			
		-0.028	-0.0003	0.064			
		Correlation coefficient					

Table 5.6: Correlation results for working points, covering the entire bias range of one transistor on GaNHFET01.

Table 5.6 shows the individual low frequency and microwave noise results for different bias conditions of a single device on waver GaNHFET01. In the first two columns the bias condition, i.e. the voltage at the gate and drain, is indicated. The following three columns hold the individual flicker noise parameters and the last three columns specify the minimum noise figure at three frequencies.

The correlation coefficient shows no frequency dependence and is close to zero independent of the selected low flicker noise parameter.

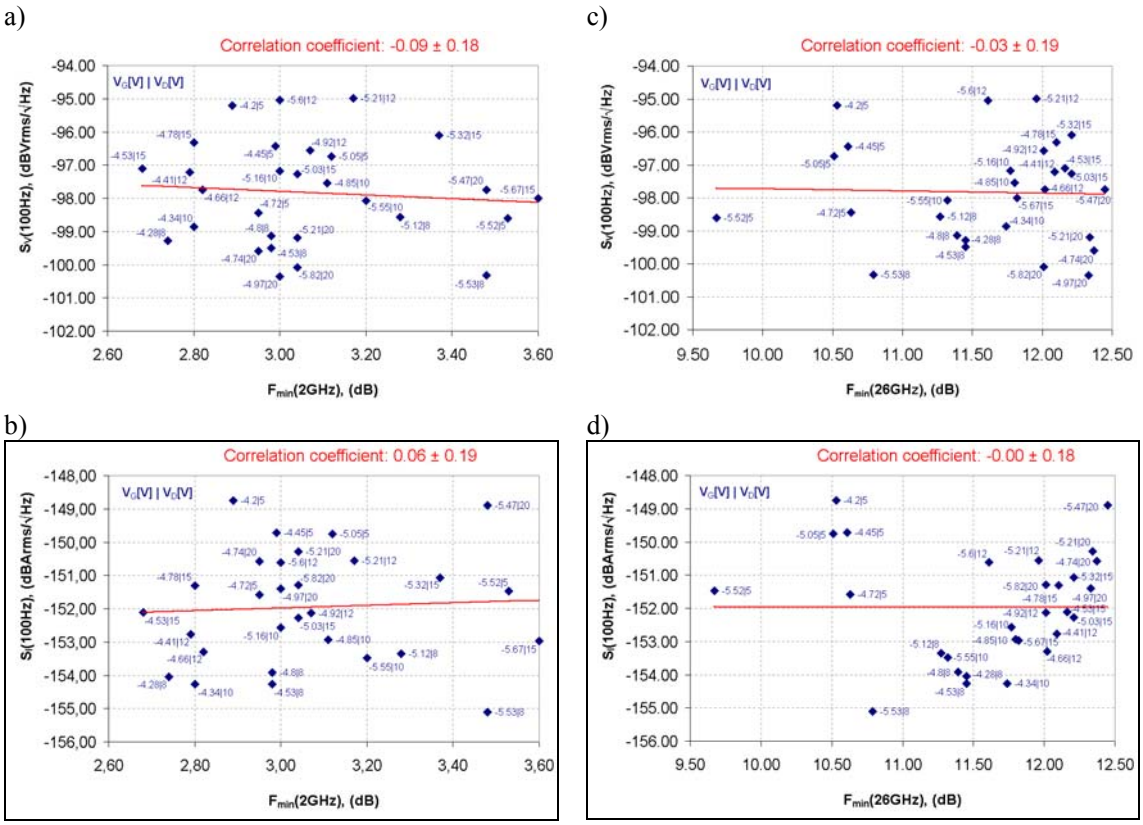


Fig. 5.20: Scatter diagrams for a comparison between the minimum noise figure F_{min} at a), b) 2 GHz and c),d) at 26 GHz and S_V and S_I at 100 Hz.

Fig. 5.20 shows again the scatter diagrams for a comparison between S_V and S_I, measured at 100 Hz and F_{min} at 2 GHz and 26 GHz. This time a dot in a diagram represents a *certain bias condition* of the *same transistor* with its corresponding F_{min} and flicker noise parameter.

As expected the microwave noise level at 26 GHz is much higher than at 2 GHz (compare *Fig. 5.5*). The constellation of points at 26 GHz seems to be shifted towards higher noise figures and cover a larger range (9.7 dB to 12.5 dB) in comparison to 2 GHz (2.7 dB to 3.6 dB).

All diagrams a) to d) show a point constellation, which support the correlation coefficient close to zero and show no association between the two noise types.

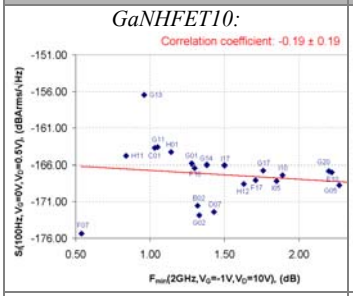
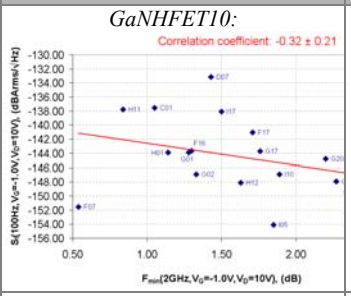
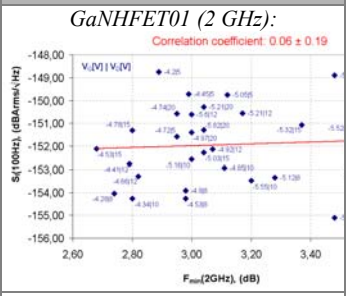
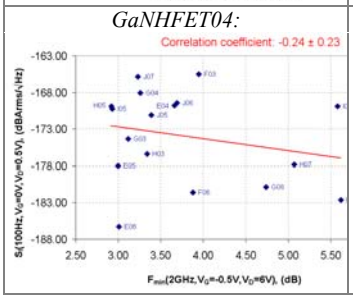
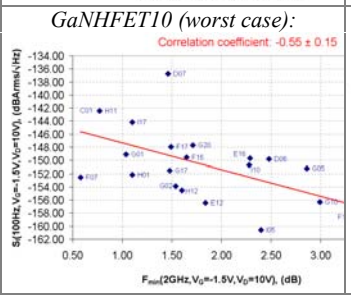
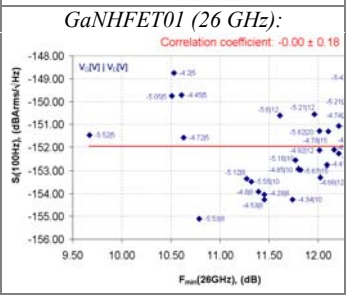
The individual results for the three presented methods will be compared to each other and a general statement concerning the topic of this investigation, if the flicker and the microwave noise of GaN HFETs is correlated, will be given in the following chapter, the conclusion.

6 CONCLUSION

The correlation between the flicker and the microwave noise of GaN HFETs at room temperature was investigated.

For this purpose a microwave system had to be assembled and put into service.

The comparison of the minimum noise figure F_{min}, which expresses the microwave noise level, with the spectral current noise density S_I, which was considered to be the most expressive parameter to refer to the flicker noise level, allows to draw the conclusion that *the flicker and the microwave noise are not correlated*.

Method A	Method B	Method C
GaNHFET10: 	*GaNHFET10:* 	*GaNHFET01 (2 GHz):* 
GaNHFET04: 	*GaNHFET10 (worst case):* 	*GaNHFET01 (26 GHz):* 

One result (Method B, GaNHFET10, worst case) yielded to a correlation coefficient of -0.56 ±0.15, but considering all reliable other cases, always a small negative correlation coefficient between -0.2 ±0.2 (Method A) and -0.3 ±0.2 (Method B) or close to zero (Method C) was obtained (*see table*).

The presented conclusion is supported by the constellation of widely spread points in the scatter diagrams, which showed no clear tendency concerning reliance between the flicker and the microwave noise.

This result indicates, that two independent noise sources are responsible for the flicker and the microwave noise. A noise model can thus be established, which describes the microwave and the flicker noise as a superposition of uncorrelated noise sources.

Appendix A: SYMBOLS AND ABBREVIATIONS

Symbol	Unit	Description
α_H		Hooge parameter
β	1/m	phase constant of the line
λ	m	wave length
φ	rad	phase of S-parameter S_{12}
σ_X		standard deviation of data set X
σ_Y		standard deviation of data set Y
Γ_{opt}		optimum complex source reflection coefficient
Γ_s		complex source reflection coefficient
F_{min}	dB	minimum noise figure
F	dB	noise figure
F_{total}	dB	total noise figure
F_{dut}	dB	noise figure of the DUT
G_a	dB	associated gain at minimum noise figure
$G_{\max}$	dB	maximum available gain (MAG)
G_{dut}	dB	available gain of the DUT
V_G	V	gate source voltage
V_D	V	drain source voltage
V_{DS_B}	V	drain source breakdown voltage
V_{meas}	V	measured voltage at the drain of the DUT
V	V	supply voltage
V_R	V	voltage drop over the resistor
V_{bat}	V	battery voltage
I_D	A	drain source current
I_G	A	gate current
I_{DS_S}	A	saturated drain source current
∂I	A	variation of the drain current
R_n	Ω	equivalent noise resistance
r_n		normalized equivalent noise resistance
R	Ω	resistance of the resistor at the drain of the DUT
R_0	Ω	mean resistance of the DUT

Symbol	Unit	Description
R_{ges}	Ω	resulting bias network resistance
r	Ω	differential resistance of the DUT
r_i	Ω	differential resistance for bias point *i*
∂r	Ω	variation of the DUT's differential resistance
r_{DC}	Ω	DC resistance of the of the DUT
P_1	Ω	resistance of the potentiometer at the drain of the DUT
P_2	Ω	resistance of the potentiometer at the gate of the DUT
S_V	V^2/Hz	spectral voltage noise density
S_I	A^2/Hz	spectral current noise density
N_{tot}		total number of charge carriers
n_s	cm^{-2}	electron sheet density
f	Hz	frequency
w	m	gate width
ℓ	m	gate length
X		data set
Y		data set
$r_{X,Y}$		correlation coefficient of data set X and data set Y
${r_{X,Y}}^2$		coefficient of determination, goodness of fit
$\mathrm{cov}_{X,Y}$		covariance of data set X and data set Y
$\bar{x}$		average of data set X
$\bar{y}$		average of data set Y
m		slope of the regression line
c		intercept of the regression line with the y-axis
c	m/s	velocity of light
P_i		bias point *i*
E_R		HP8510 error coefficient, representing the frequency response
E_D		HP8510 error coefficient, representing the directivity
E_S		HP8510 error coefficient, representing the source match
$\mathbf{A}_S$		S-parameter matrix, describing the error adapter of the first calibration
$\mathbf{A}_T$		chain matrix transformed matrix $\mathbf{A}_S$
$\mathbf{B}_S$		S-parameter matrix, describing the fixture
$\mathbf{B}_T$		chain matrix transformed matrix $\mathbf{B}_S$
$\mathbf{C}_S$		S-parameter matrix, describing error adapter of the second calibration
$\mathbf{C}_T$		chain matrix transformed matrix $\mathbf{C}_S$
ℓ	m	electrical length of a line
Z_0	Ω	reference impedance of the system (50 Ω)

Abbreviation	Meaning
ALFNM	**A**utomated **L**ow **F**requency **N**oise **M**easurement
AlGaN	**Al**uminum **Ga**llium **N**itride
AlN	**Al**uminum **N**itride
ATS	**A**utomated **T**uner **S**ystem (Maury Microwaves)
DUT	**D**evice **U**nder **T**est
FET	**F**ield **E**ffect **T**ransistor
FFT	**F**ast **F**ourier **T**ransformation
GaAs	**Ga**llium **A**rsenide
GaN	**Ga**llium **N**itride
GPIB	**G**eneral **P**urpose **I**nstrument **B**us
HBT	**H**eterojunction **B**ipolar **T**ransistor
HEMT	**H**igh **E**lectron **M**obility **T**ransistor
HFET	**H**eterostructure **F**ield **E**ffect **T**ransistor
HJFET	**H**eterojunction **F**ield **E**ffect **T**ransistor
JFET	**J**unction **F**ield **E**ffect **T**ransistor
LF	**L**ow **F**requency
MESFET	**M**etal **E**pitaxial **S**emiconductor **F**ield **E**ffect **T**ransistor
MHEMT	**M**etamorphic **H**igh **E**lectron **M**obility **T**ransistors
MISFET	**M**etal **I**nsulator **S**emiconductor **F**ield **E**ffect **T**ransistor
MMIC	**M**onolithic **M**icrowave **I**ntegrated **C**ircuit
MODFET	**M**odulation **D**oped **S**emiconductor **F**ield **E**ffect **T**ransistor
MOSFET	**M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor
MW	**M**icro**w**ave
PHEMT	**P**seudomorphic **H**igh **E**lectron **M**obility **T**ransistor
PHFET	**P**seudomorphic **H**eterojunction **F**ield **E**ffect **T**ransistor
PSD	**P**ower **S**pectral **D**ensity
SDHFET	**S**electively **D**oped **H**eterostructure **F**ield **E**ffect **T**ransistor
SiC	**Si**licon **C**arbide
TEGFET	**T**wo **D**imensional **E**lectron-**G**as **F**ield **E**ffect **T**ransistor
VNA	**V**ector **N**etwork **A**nalyzer

Appendix B: DERIVATIONS FOR THE FLICKER NOISE

B.1 Derivation of the Equation relating S_I with S_V

The spectral voltage noise density S_V, measured at the drain of a biased transistor depends on the following drain bias network, which is changing if the voltage is adjusted.

Therefore the spectral current noise density S_I is calculated from S_V to have a common base to compare measurement results. Further, in papers this parameter is mainly used to characterize the flicker noise level and the results of this investigation can be easier compared to results referenced in publications.

B.1.1 Linear region

If a field effect transistor is operating in the linear region, it can be considered as a voltage controlled resistor r.

If we consider the voltage V and the value of the resistor R_{res} as constant, a variation ∂r of the resistor r will lead to a variation ∂I, due to Ohm's law.

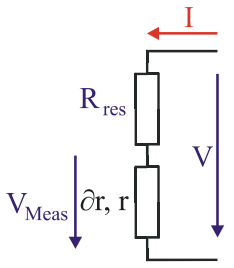


Fig. B.1: Simplified circuit to derive the relation between S_I and S_V.

The resistor network in *Fig. B.1* shows a voltage divider, formed by r and R_{res}. V_{meas} can be expressed by

$$V_{meas} = \frac{V \cdot r}{R_{res} + r} . \tag{B.1}$$

If we calculate the derivative of (B.1) with respect to r we get

$$\frac{\partial V_{meas}}{\partial r} = \frac{V}{R_{res} + r} - \frac{V \cdot r}{(R_{res} + r)^2} = \frac{V \cdot (R_{res} + r) - V \cdot r}{(R_{res} + r)^2} = \frac{V \cdot R_{res}}{(R_{res} + r)^2} . \tag{B.2}$$

Solved for ∂r and divided by r, equation (B.2) can be written as

$$\frac{\partial r}{r} = \frac{\partial V_{meas}}{V} \cdot \frac{(R_{res} + r)^2}{R_{res} \cdot r} . \tag{B.3}$$

If we insert (B.1) in (B.3) we get

$$\frac{\partial r}{r} = \frac{\partial V_{meas}}{V_{meas}} \cdot \frac{R_{res} + r}{R_{res}} . \tag{B.4}$$

For the short circuit current fluctuation, we can write

$$\frac{\partial I}{I} = \frac{\partial r}{r} = \frac{\partial V_{meas}}{V_{meas}} \cdot \frac{R_{res} + r}{R_{res}} . \tag{B.5}$$

If we solve (B.5) for ∂I with

$$V_{meas} = R_{res} \cdot I , \tag{B.6}$$

square both sides of the equation and divide by Δf, we get

$$\frac{\partial I^2}{\Delta f} = \frac{\partial V_{meas}{}^2}{\Delta f} \cdot \left(\frac{R_{res} + r}{R_{res} \cdot r} \right)^2 . \tag{B.7}$$

The expression in (B.7) can be written as

$$\boxed{S_I = S_V \cdot \left(\frac{R_{res} + r}{R_{res} \cdot r} \right)^2} , \tag{B.8}$$

with S_I, the spectral current noise density and S_V, the spectral voltage noise density [1].

B.1.2 Saturation region

Expression (B.8) can also be written in the form

$$S_I = S_V \cdot \left(\frac{1}{R_{res}} + \frac{1}{r} \right)^2 . \tag{B.9}$$

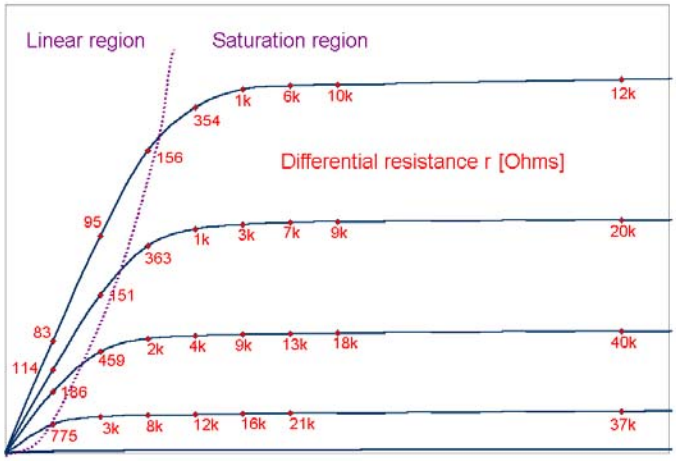


Fig. B.2: Differential resistance in the linear and saturation region.

In the saturation region the differential resistance r is much higher than in the linear region (*Fig. B.2*). If $r >> R_{res}$ the second term in (B.9) can be neglected and the equation can be written as

$$\boxed{S_I = S_V \cdot \frac{1}{R_{res}^2}} . \tag{B.10}$$

B.2 Estimation of R_{res} for the present measurement system

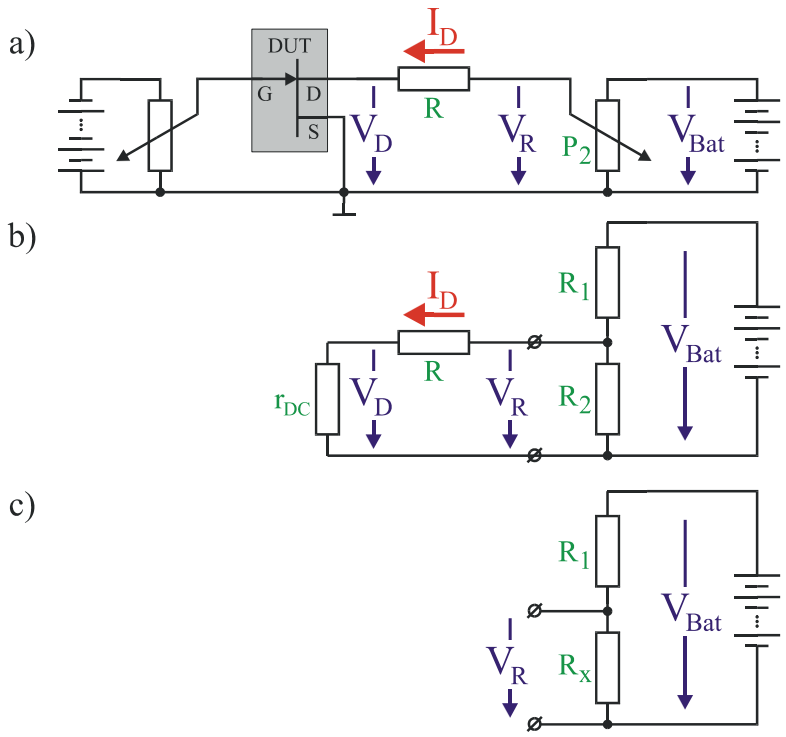


Fig. B.3: Derivation of all parameters by the measured voltages and known resistors.

A schematic drawing of the noise measurement setup is shown in *Fig. B.3a*. The resistance of R and the potentiometer P_2 are known and the voltages V_D, V_R and V_{bat} are determined for each noise measurement.

The drain source current I_D can be estimated by the expression

$$I_D = \frac{V_R - V_D}{R} \tag{B.11}$$

and with this result the DC resistance r_{DC} of the FET can be determined

$$r_{DC} = \frac{V_D}{I_D}. \tag{B.12}$$

The potentiometer P_2 can be replaced by two resistors R_1 and R_2 (*Fig. B.3b*), which are related by

$$P_2 = R_1 + R_2 \,. \tag{B.13}$$

r_{DC}, R_2 and R can be united to the resistor R_x (*Fig. B.3c*), which is given by

$$R_x = \frac{(r_{DC} + R) \cdot R_2}{r_{DC} + R + R_2} \,. \tag{B.14}$$

R_1 and R_x form a voltage divider and the resistance of R_1 can be calculated by

$$R_1 = \frac{V_{bat}}{V_R} \cdot R_x - R_x \,. \tag{B.15}$$

Inserting (B.13) and (B.14) into (B.15) and solving for R_1, we obtain the equation

$$\begin{aligned} R_1 = {} & \frac{1}{2 \cdot V_R} \cdot (V_{bat} \cdot R + V_{bat} \cdot r_{DC} + V_R \cdot P_2 \\ & + \sqrt{\begin{aligned} & {V_R}^2 \cdot {P_2}^2 + {V_{bat}}^2 \cdot R^2 + {V_{bat}}^2 \cdot {r_{DC}}^2 \\ & - 2 \cdot V_R \cdot V_{bat} \cdot R \cdot P_2 - 2 \cdot V_R \cdot V_{bat} \cdot r_{DC} \cdot P_2 \\ & + 2 \cdot {V_{bat}}^2 \cdot R \cdot r_{DC} + 4 \cdot {V_R}^2 \cdot R \cdot P_2 + 4 \cdot {V_R}^2 \cdot r_{DC} \cdot P_2 \end{aligned}} \,) \end{aligned} \tag{B.16}$$

This equation consists only of known or measured quantities and can thus be solved.
R_2 can then be determined from (B.13)

$$R_2 = P_2 - R_1 \,. \tag{B.17}$$

With this result the network in *Fig. B.3a* can be transformed to that of *Fig. B.1* with

$$\boxed{R_{res} = R + \frac{R_1 \cdot R_2}{R_1 + R_2}} \,. \tag{B.18}$$

B.3 Estimation of the differential resistance r

Spontaneous fluctuations in current and voltage is referred to as noise. Thus it is no static but a time dependent process. To estimate the resistance of the device under test, a linear approximation in its working point is made. *Fig. B.4* shows a sector of an IV-Curve (blue curve) with the red dots representing the discrete measured points of the drain current I_D versus drain voltage V_D.

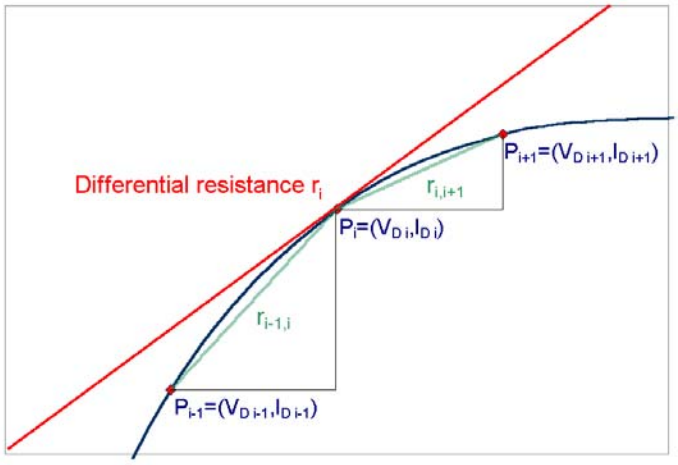


Fig. B.4: Calculation of the differential resistance r_i in the bias point P_i.

The resulting differential resistance r_i for the bias point P_i can be calculated by the relation:

$$r_i = \frac{r_{i-1,i} + r_{i,i+1}}{2}, \tag{B.19}$$

with

$$r_{i-1,i} = \frac{V_{Di} - V_{Di-1}}{I_{Di} - I_{Di-1}} \tag{B.20}$$

and

$$r_{i,i+1} = \frac{V_{Di+1} - V_{Di}}{I_{Di+1} - I_{Di}}. \tag{B.21}$$

Appendix C: CORRELATION

If a dependence of two data ranges (in our case the parameter, representing the noise level of the flicker noise and the microwave noise) is not directly perceptible, a mathematical approach can help to identify the degree of reliance between the two ranges. The correlation coefficient is such a mathematical aid and a short overview will be given how it was applied to analyze the data.

C.1 The Correlation Coefficient

The correlation coefficient is a measure to compare, if two ranges of data X and Y are dependent on each other. That is, whether large values of one set are associated with large values of the other (positive correlation, correlation coefficient $r_{X,Y}$ = 1), whether small values of one set are associated with large values of the other (negative correlation, $r_{X,Y}$ = -1), or whether values in both sets are unrelated (correlation near zero, $r_{X,Y}$ = 0).

The correlation coefficient is defined as the covariance of two data sets X and Y divided by the product of their standard deviations [29]

$$r_{X,Y} = \frac{\mathrm{cov}_{X,Y}}{\sigma_X \cdot \sigma_Y}, \tag{C.1}$$

with the covariance defined as

$$\mathrm{cov}_{X,Y} = \frac{1}{n} \cdot \sum_{i=1}^{n} (x_i - \bar{x}) \cdot (y_i - \bar{y}) \tag{C.2}$$

and the standard deviations defined as

$$\sigma_X = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n}}, \; \sigma_Y = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n}}. \tag{C.3}$$

n indicates the number of points in the data range.

Equations (C.2) and (C.3) contain the average or mean $\bar{x}$ and $\bar{y}$ of the two data ranges, which can be calculated by

$$\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i \ , \ \bar{y} = \frac{1}{n} \cdot \sum_{i=1}^{n} y_i \ . \tag{C.4}$$

C.2 Least Square Regression

To visualize a dependence of two data ranges, one range is plotted versus the other in a so-called *scatter diagram* (*Fig. C.1*).

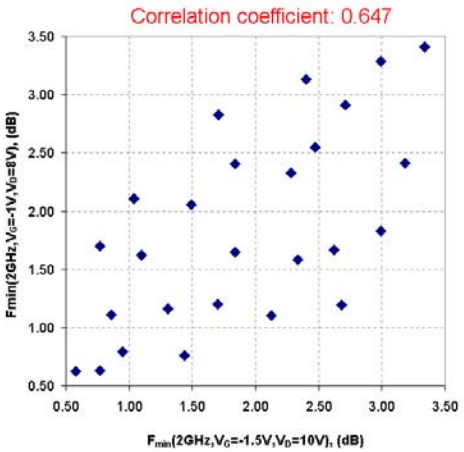


Fig. C.1: Example of a scatter diagram.

An intuitive idea of finding a linear approximation of the relationship between the independent and dependent variables can be obtained by drawing a line that is chosen to minimize the squared distances between the points and the line (*Fig. C.2*).

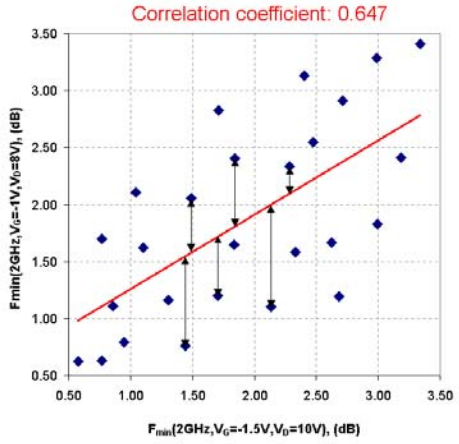


Fig. C.2: The least squares line minimizes the squared distances between the line and the points.

The line is given [29] by

$$y = m \cdot x + c\,, \tag{C.5}$$

with the slope m calculated by

$$m = \frac{\mathrm{cov}_{X,Y}}{\sigma_X} \tag{C.6}$$

and the intercept with the y-axis

$$c = \bar{y} - m \cdot \bar{x}\,. \tag{C.7}$$

C.3 Observation range

If a dependence of two measurement sets should be analyzed, it is also important to know the possible range of the parameters. To illustrate this idea, two graphs are shown in *Fig. C.3*. The left picture shows an example, where measurement results cover the entire range of possible values. In this case a correlation coefficient close to 1 is obtained. If the same graph is taken, but only a sector is considered (*Fig. C.3b*), the correlation coefficient drops to a much smaller value.

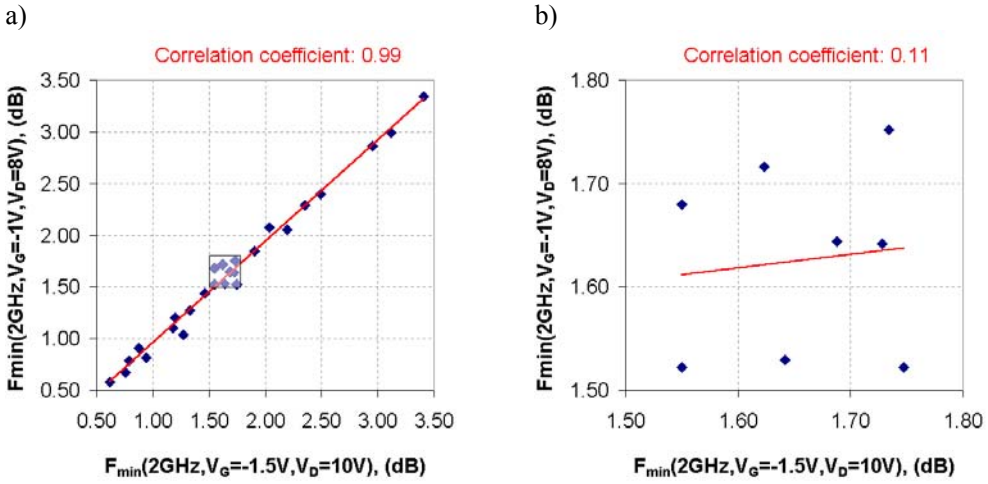


Fig. C.3: Different correlation results dependent on the chosen range. a) Entire range b) small sector.

In practice the parameter range is sometimes unknown or the measurement results occur only in a limited range. In this case, a misinterpretation of the obtained result gets very likely.

C.4 The Coefficient of Determination

The regression line is defined to be the line, lying closest to the data points. It is often useful to be able to evaluate how close the line approximate the points, what is often referred to as the *goodness of fit* of the regression line.

Fig. C.4 shows a comparison of two scatter plots with regression lines with the same slope. Although both diagrams have the same regression line, the left is referred to have a better fit than the other, because the points are closer to the line.

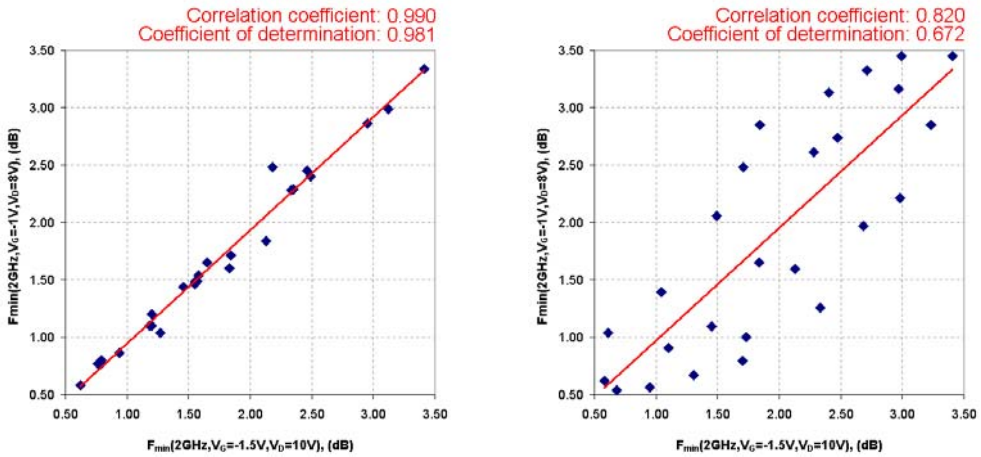


Fig. C.4: Comparison of goodness of fit for two regression lines with the same slope.

The measure of relative closeness for evaluating the goodness of fit is called the *coefficient of determination*. Because of its relationship to the correlation coefficient, this measure is generally referred to as the $r_{X,Y}{}^2$. (The coefficient of determination is the square of the correlation coefficient.) It describes the proportion of variance in common between the two variables. If we multiply this by 100, we get the percentage of variance in common.

C.5 Error due to small number of observations

The error due to a small number of observations can be calculated [30] by

$$\sigma_r = \frac{1 - r_{X,Y}{}^2}{\sqrt{n}}, \tag{C.8}$$

with n the number of observations. The correlation coefficient can thus be written as

$$\boxed{r_{res} = r \pm \sigma_r}. \tag{C.9}$$

Appendix D: WAVER INFORMATION

D.1 GaNHFET01

The high frequency properties of these devices were measured at *Raytheon Corporation* in a frequency range from 2 GHz to 26 GHz.

D.1.1 Typical material properties

Mobility: 1000 cm2/Vs

Carrier sheet density: $1x10^{13}$ cm-2

Aluminum mole fraction: 15%

Surface passivation: No

Process: MOCVD (low pressure)

D.1.2 Layer structure

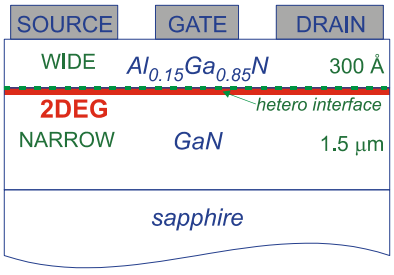


Fig. D.1: Layer structure of GaNHFET01.

D.1.3 Typical DC-characteristics

A typical output characteristic and typical gate leakage current is shown in *Fig. D.2* for a transistor (6,3) on waver GaNHFET01.

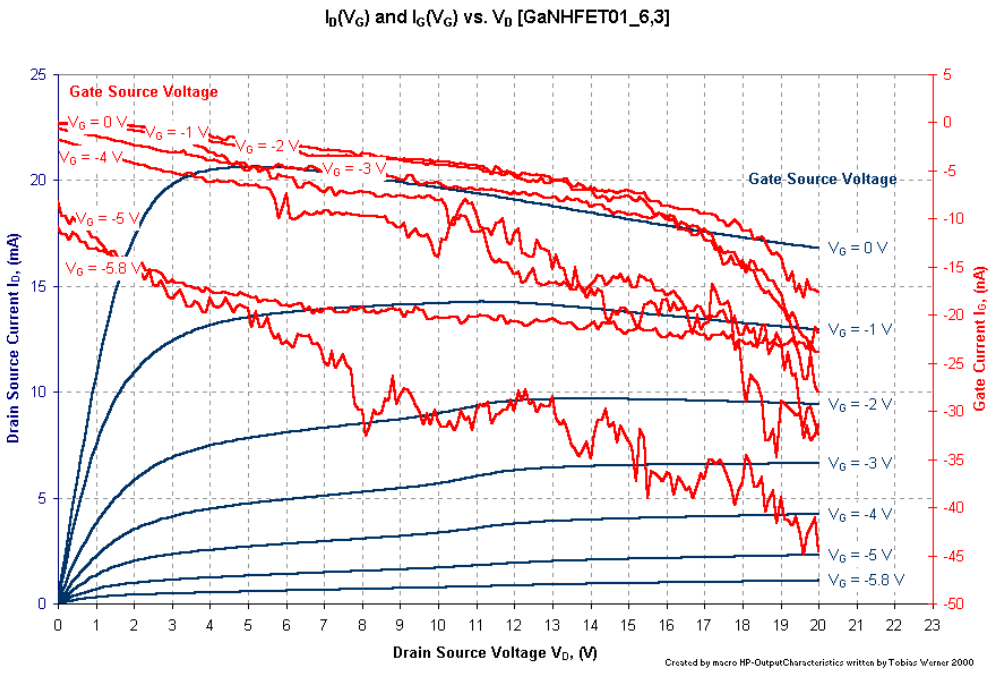

$I_D(V_G)$ and $I_G(V_G)$ vs. V_D [GaNHFET01_6,3]
Gate Source Voltage
V_G = 0 V
V_G = -1 V
V_G = -2 V
V_G = -3 V
V_G = -4 V
V_G = -5 V
V_G = -5.8 V
Gate Source Voltage
V_G = 0 V
V_G = -1 V
V_G = -2 V
V_G = -3 V
V_G = -4 V
V_G = -5 V
V_G = -5.8 V
Drain Source Current I_D, (mA)
Gate Current I_G, (nA)
Drain Source Voltage V_D, (V)
Created by macro HP-OutputCharacteristics written by Tobias Werner 2000

Fig. D.2: Typical IV-Curve for GaNHFET01.

D.1.4 Waver map

Transistors marked red were working devices. The DC-characteristics, S-parameters, and the flicker and microwave noise were measured for these devices. All other device, were either working, but had differing properties, or were not analyzed.

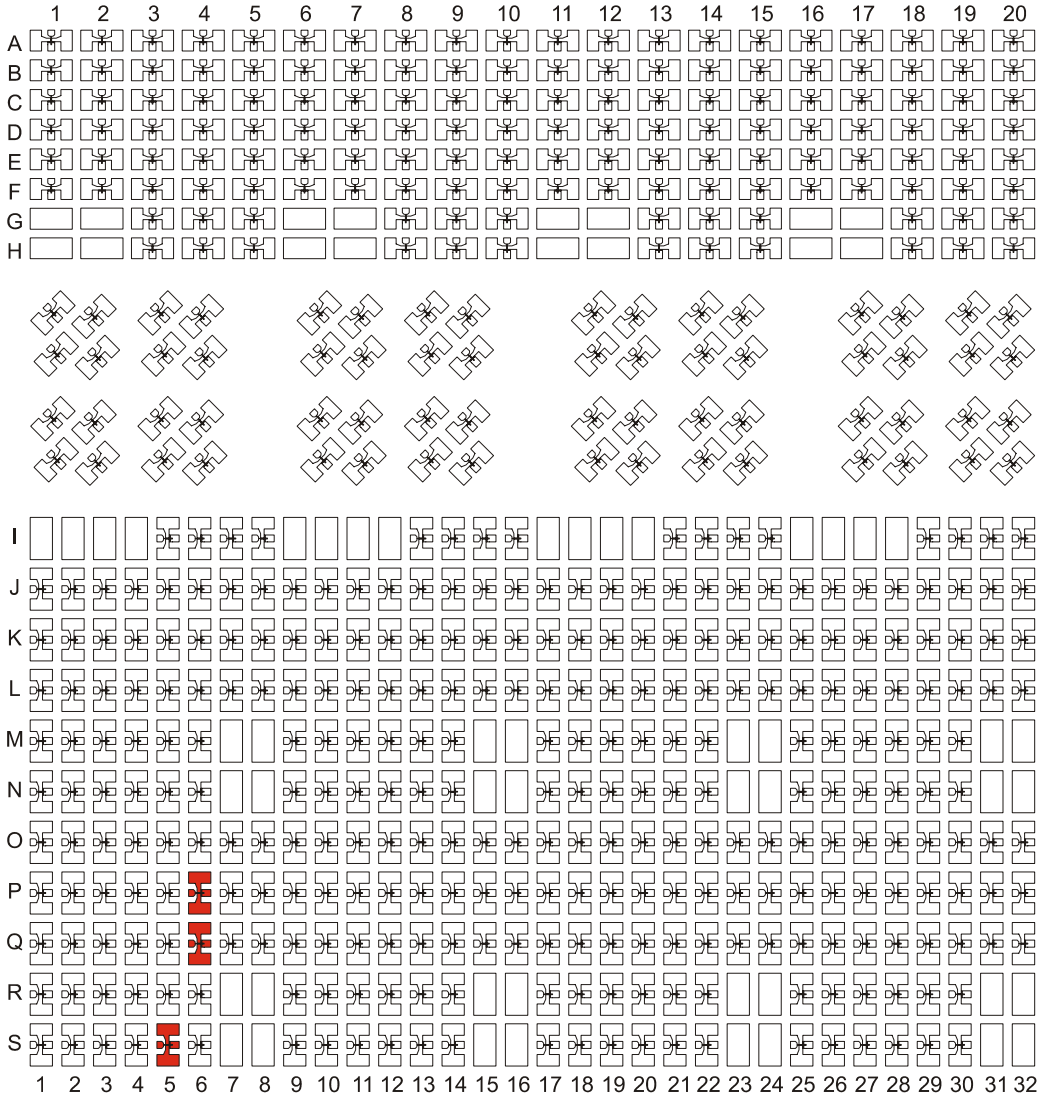


Fig. D.3: Waver map of GaNHFET01.

D.2 GaNHFET04

D.2.1 Typical material properties

Mobility 1000 cm2/Vs

Carrier sheet density: $1x10^{13}$ cm-2

Aluminum mole fraction: 15-20%

Surface passivation: No

Process: MOCVD (low pressure)

D.2.2 Layer structure

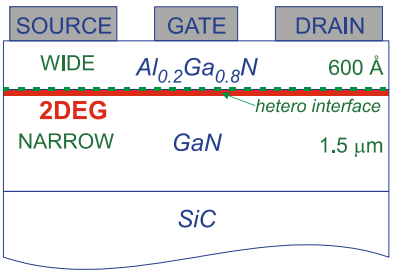


Fig. D.4: Layer structure of GaNHFET04.

D.2.3 Typical DC-characteristics

A typical output characteristic and typical gate leakage current is shown in *Fig. D.5* for a transistor (J07) on waver GaNHFET04.

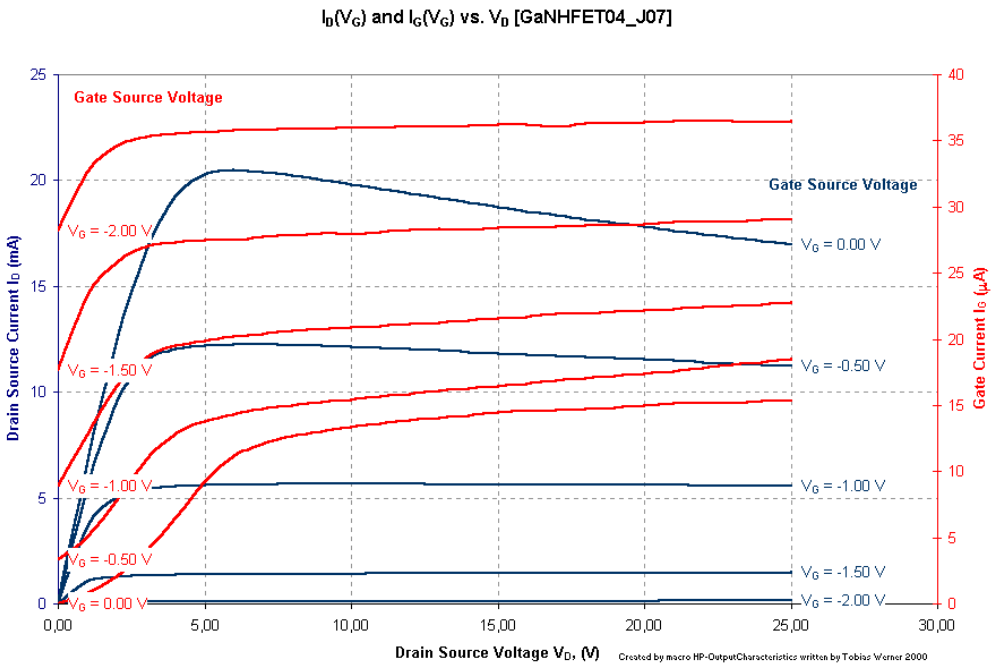


Fig. D.5: Typical I-V-curve for GaNHFET04.

D.2.4 Waver map

Transistors marked red were working devices. The DC-characteristics, S-parameters, and the flicker and microwave noise were measured for these devices. Devices marked gray, were not working. All other device, were either working, but had differing properties, or were not analyzed.

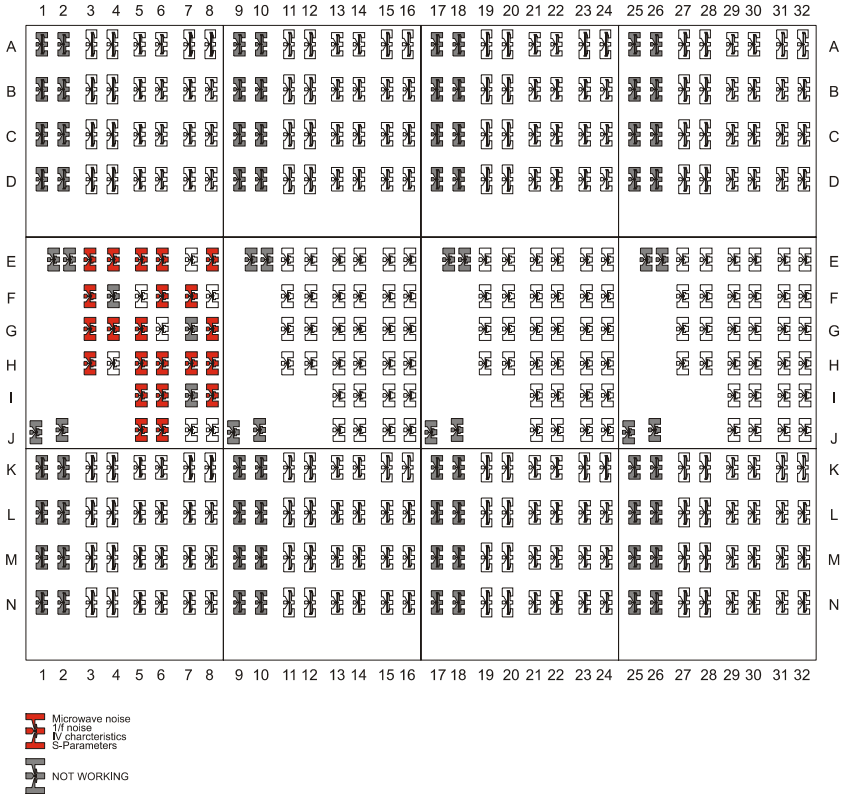

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
A B C D E F G H I J K L M N
Microwave noise
1/f noise
IV charcteristics
S-Parameters
NOT WORKING

Fig. D.6: Map of the waver GaNHFET04.

D.3 GaNHFET08

D.3.1 Typical material properties

Mobility 1400 cm2/Vs

Carrier sheet density: 1.1×10^{13} cm-2

Aluminum mole fraction: 15%

Surface passivation: No

Process: MOCVD (low pressure)

D.3.2 Layer structure

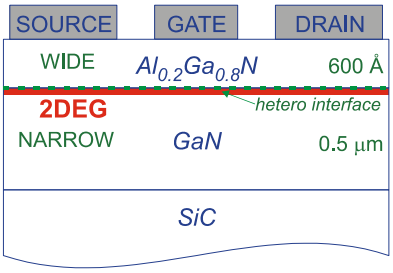


Fig. D.7: Layer structure of GaNHFET08.

D.3.3 Typical DC-characteristics

A typical output characteristic and typical gate leakage current is shown in *Fig. D.8* for a transistor (C12) on waver GaNHFET08.

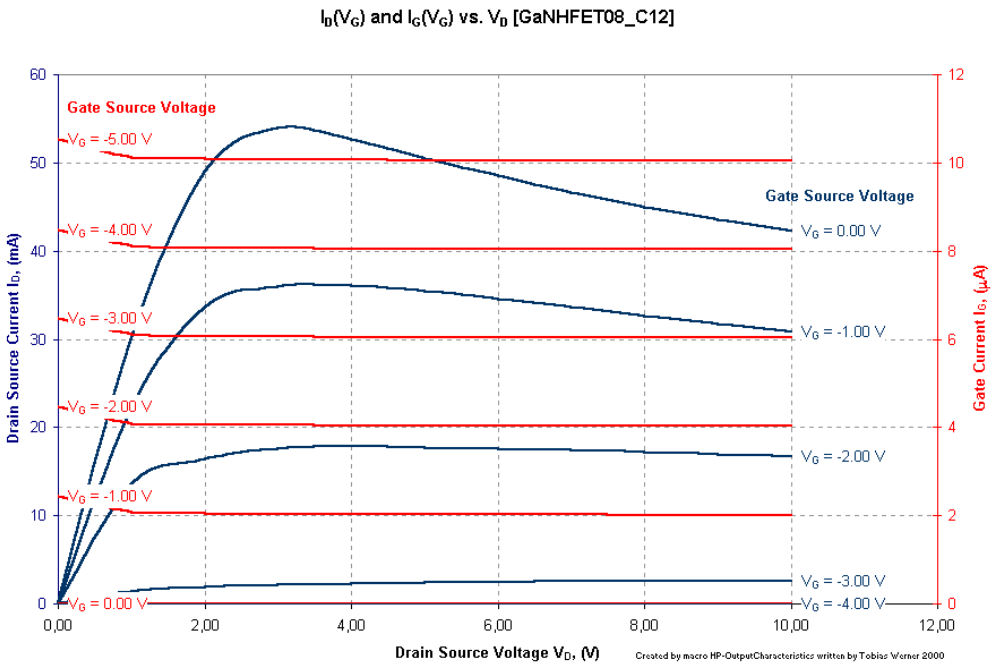


Fig. D.8: Typical I-V-curve for GaNHFET08.

D.3.4 Waver map

Transistors marked red were working devices. The DC-characteristics, S-parameters, and the flicker and microwave noise were measured for these devices. Devices marked gray, were not working. All other device, were either working, but had differing properties, or were not analyzed.

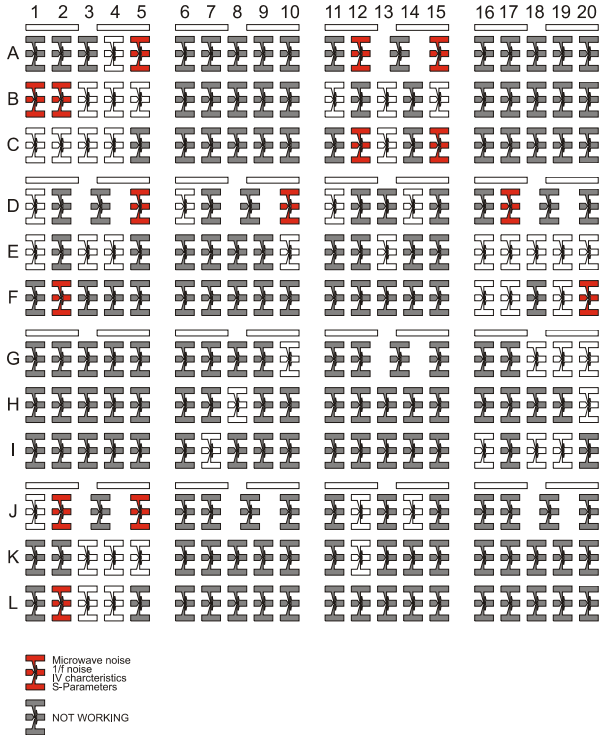


Fig. D.9: Map of the waver GaNHFET08.

D.4 GaNHFET10

The microwave noise on this waver was the lowest of all measured wavers.

D.4.1 Typical material properties

Mobility 1400 cm2/Vs

Carrier sheet density: 1.1x1013 cm-2

Aluminum mole fraction: 15-20%

Surface passivation: No

Process: MOCVD (low pressure)

D.4.2 Layer structure

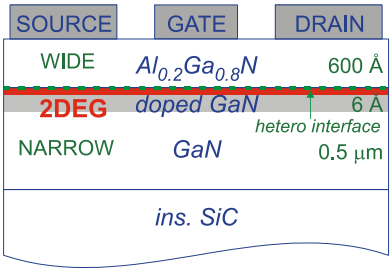


Fig. D.10: Layer structure of GaNHFET10.

D.4.3 Typical DC-characteristics

A typical output characteristic and typical gate leakage current is shown in *Fig. D.11* for a transistor (F07) on waver GaNHFET10.

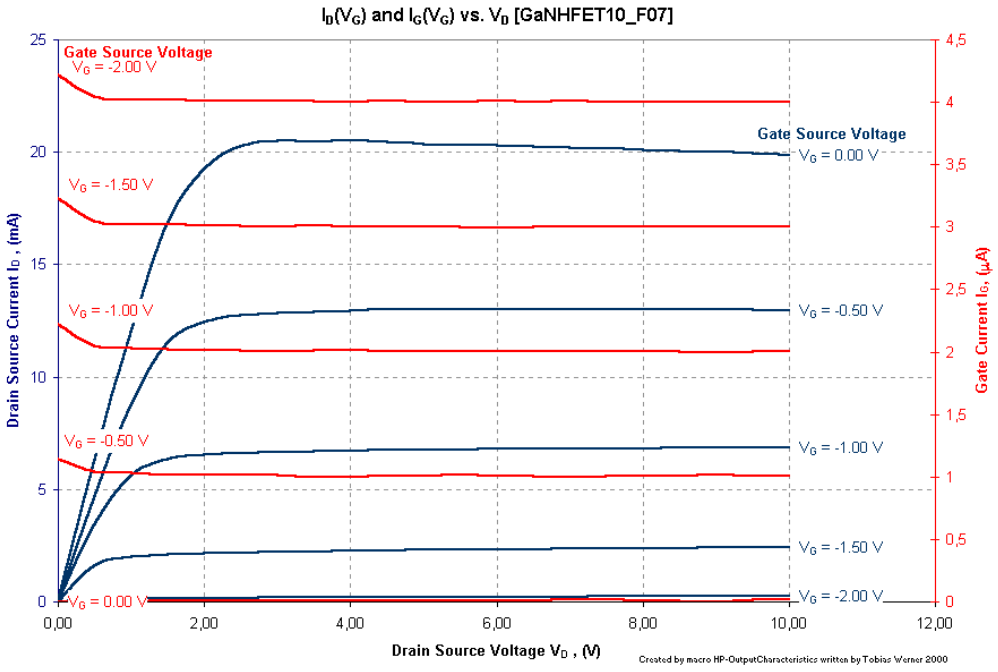


Fig. D.11: Typical I-V-curve for GaNHFET10.

D.4.4 Noise and gain parameters

The transistor F07 on waver GaNHFET109 had the lowest measured noise level and the noise properties of this transistor will be therefore mentioned.

Fig. D.12 shows the noise parameters and different gains as a function of the selected bias condition. The minimum noise figure F_{min}, the relative noise resistance r_n, the associated gain at minimum noise figure G_a and the maximum available gain G_{max} are specified for each working point of the analyzed transistor. The optimum source reflection coefficient is also indicated as a red dot in a small smith chart.

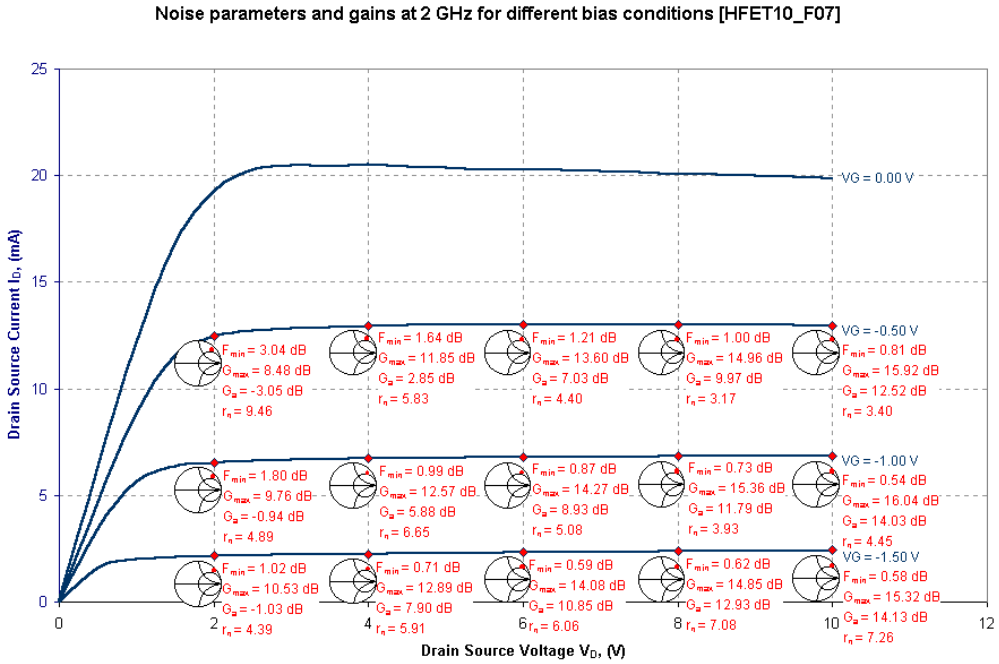

Noise parameters and gains at 2 GHz for different bias conditions [HFET10_F07]
Drain Source Current I_D, (mA)
Drain Source Voltage V_D, (V)
VG = 0.00 V
VG = -0.50 V
VG = -1.00 V
VG = -1.50 V

Fig. D.12: Noise parameters and gains of GaNHFET10_F07.

D.4.5 Waver map

Transistors marked red were working devices. The DC-characteristics, S-parameters, and the flicker and microwave noise were measured for these devices. Devices marked gray, were not working. All other device, were either working, but had differing properties, or were not analyzed.

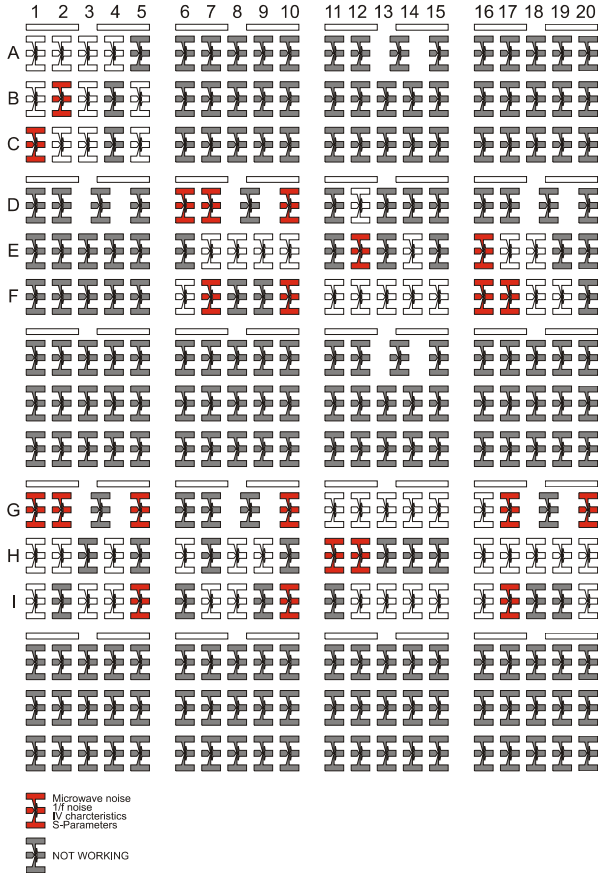


Fig. D.13: Map of the waver GaNHFET10.

Appendix E: LOW FREQUENCY NOISE MEASUREMENT PROGRAM

Before the program was created, the low frequency noise measurement was very time consuming and complicated. Fortunately, the SR770 is equipped with a GPIB[9] interface and can be therefore controlled by a host computer, equipped with a GPIB card.

The program provides a *Windows* compatible user interface, where measurement parameters can be set and it is intended to automate the entire measurement process.

According to the settings in the interface, the measurement is divided into several sub sections. The parameters are transferred to the instrument and the measurement is started. When the measurement for a single section has ended, the measurement results are transmitted back to the computer, the parameters are adjusted for the next section and the measurement process starts again. When the last measurement section has passed, the results are transferred to the host computer and all single measurement results are combined to one data file, which is then stored on hard disk.

A macro for *Microsoft Excel,* written in *Visual Basic for Applications* accesses the data file and displays the entire measurement result.

The following chapters describe roughly the implementation of the program and the user interface. It was not the main topic of the Diploma thesis to create this program and the documentation will therefore only give a brief overview.

E.1 Smoothing of the graph

The FFT spectrum analyzer SR770 is only capable of measuring at equidistant linear frequency steps. If the acquired data is then plotted versus a logarithmic frequency scale, the density of measurement points increases for higher frequencies, without providing additional information about the qualitative course of the graph (blue graph, *Fig. E.1*). The program *Automated Low Frequency Noise Measurement* takes this into account and provides an option to reduces the overhead of information in the higher frequency band. If selected, only relevant samples in a logarithmic reference frequency interval are taken. (red graph, *Fig. E.1*).

[9] General Purpose Instrument Bus

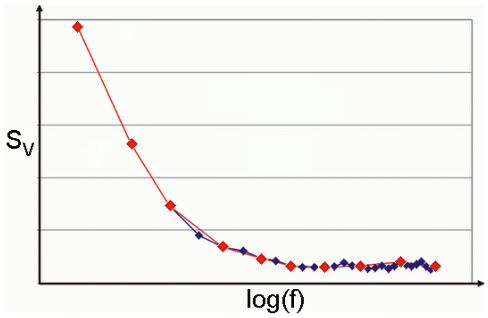


Fig. E.1: Comparison between the original (blue) and the converted data (red).

The low frequency noise was measured from 1 Hz to 100 kHz. As described before, the entire graph consists of several single measurements in order to accurately describe as well the lower part of the spectrum.

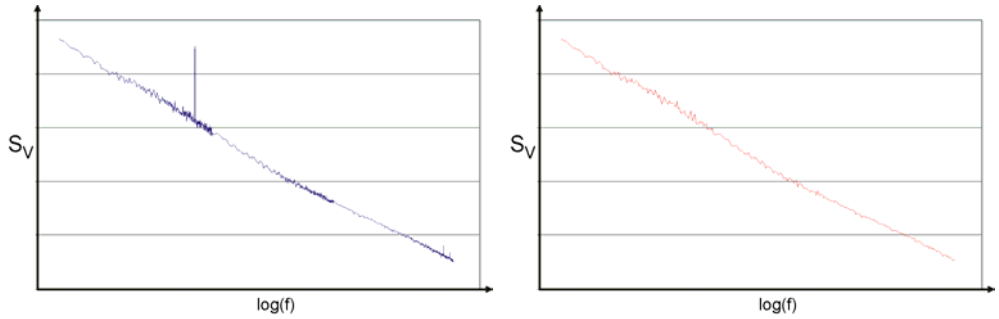


Fig. E.2: Comparison between combined sections of measurements taken at linear (left, blue) and logarithmic (right, red) equidistant steps.

If measurement sections have to be combined the graph will show steps, due to a continual increase and a sudden decrease of information, when the next measurement section begins. This case is illustrated in the left graph of *Fig. E.2* for three frequency sections. The right picture shows the same graph, if the presented algorithm, which eliminates redundant measurement points, is used. The graph now looks smooth like a single measurement.

E.2 Design of the program

The program is written in Microsoft Visual C++ 6.0 and communicates with the instrument over the GPIB. It is designed as a multithreading application and the measurement can be as a result interrupted at any time. This is important due to the fact that measurements can take a long time and there should be a possibility to stop and restart it, if a wrong setting or a sudden perturbation is discovered.

Very convenient is that the time until the predicted end of the measurement is displayed in the status bar of the program. Especially if long measurements are taken, this makes it easy to leave the setup unattended and to come back right when the measurement has finished.

All parameters are examined for wrong settings and items in the interface are enabled or disabled depending on the interaction with the user, to make wrong program handling impossible. A main rule was that the program had to be intuitive. Therefore the user interface was designed with great care and can be seen in *Fig. E.3*.

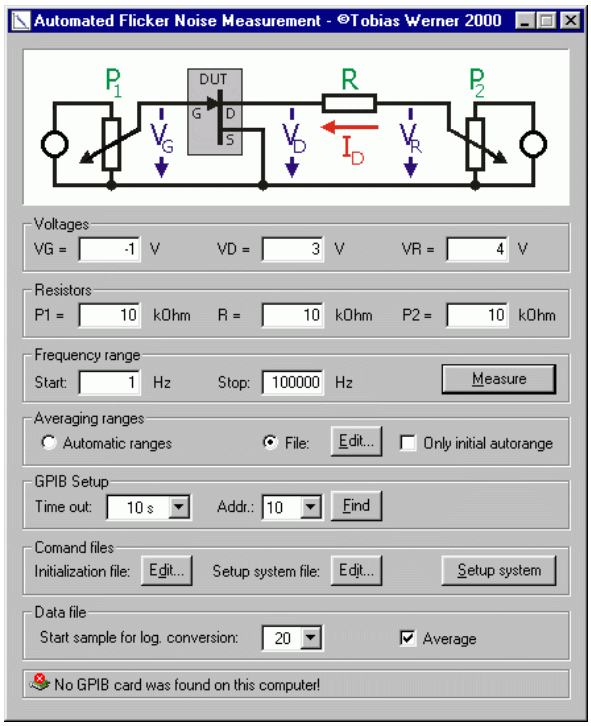


Fig. E.3: The user interface of the automated low frequency noise measurement program.

The interface of the dialog-based program is divided into the categories *Voltages*, *Resistors*, *Frequency range*, *Averaging ranges*, *GPIB Setup*, *Command files* and *Data file*. A schematic diagram of the measurement setup shows where the corresponding voltages are measured and resistors are located. The measurement range can be defined with a start and stop frequency and will be split up into several sections, depending on the setting in the category *Averaging ranges*. An automatic or a file-based solution can be chosen and will decide how many sections will be used and what averaging will be applied in these sections.

In the next category the GPIB time out and GPIB address can be adjusted. To set up the system easier, a scan function has been implemented, which scans the GPIB bus for the name string of the SR770 and changes the address accordingly, if the instrument was found.

The initialization and setup procedure of the analyzer is not fixed and can be altered in a file.

To reduce the overhead of redundant information, an algorithm was implemented to convert data points from an equidistant linear to an equidistant logarithmic scale. The start sample for this conversion and if the values should be averaged can be selected.

Fig. E.4: Expressive icons are used to reflect the status of the program. Their meaning from left to right: GPIB card search, GPIB card found, GBIP card failure, SR770 search, SR770 found, SR770 failure, SR770 warning, SR770 save data, SR770 measurement, SR770 measurement interrupted, SR770 measurement completed, SR770 setup ready, SR770 transferring data, general information, general question.

Help messages for all parameters and the progress of the measurement are displayed in the status bar of the program. Icons help to illustrate, if the messages are related to the GBIB card, the SR770 or if it is a general hint or question. Some of the icons can be seen in *Fig. E.4*.

E.3 Manual

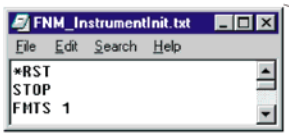
Automated Low Frequency Noise Measurement V1.0

Static Settings:
The voltage and resistor settings have no influence on the measurement process and are only written to the data file for further reference.
The value of VG and VD will be used as a part of the file name.

Measurement range:
The start and stop frequency determine the frequency range of the measurement.
The start and stop frequency will be used as a part of the file name.

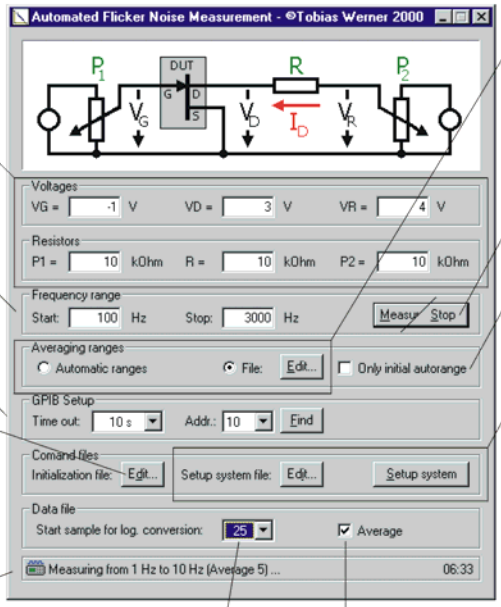
GPIB settings:
The time out indicates the time, the GPIB interface will wait for a command to succeed. If the instrument does not respond, the program will be aborted and an error message will be shown. The standard value for this parameter is 10s.
The address should be adjusted to the GPIB address of the instrument. The standard setting is 10. Use the **Find button** to scan for the address of the SR770.

Initialization file:
If you push this **Edit button**, the initialization file will open. This file contains GPIB commands for the SR770 (refer manual chapter 6) to initialize the instrument. You can adjust the initialization procedure by adding or deleting commands. The commands are executed once, if the **Measure button** is pushed.

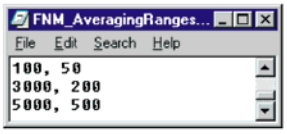


Event bar:
Displays help, the status of the program and the time until end of measurement.

General:
This program is used to control the Spectrum Analyzer SR770 of Stanford Research Systems. It communicates with the instrument by sending commands and receiving data over the GPIB bus.
After measurement is completed, it stores the measurement data into two files. One file is a raw data file and contains the untreated measurement values. Its file name consists of the voltages VG and VD, the measured frequency range and the appended text "_raw", e.g.
Vd=3.00V,Vg=-1.00V,start=1.0Hz,stop=100000.0Hz_raw.txt
The other file contains converted data which is adjusted to equidistant steps in the logarithmic frequency scale.
The file name is created as before, except the appended text:
Vd=3.00V,Vg=-1.00V,start=1.0Hz,stop=100000.0Hz.txt.
The data files are stored in the same directory as the program is located.



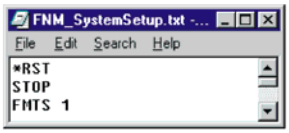
Averaging ranges:
You can either select automatic or manual ranges for the averaging of the SR770. In the automatic mode the program will estimate the frequency steps and applied number of averages automatically, depending on the selected frequency range. The File option is more flexible and you can decide in how many frequency steps the measurement range should be divided and what averaging factor should be used in these ranges.
The format should be
frequency, averaging
It expresses what averaging should be used below the indicated frequency.



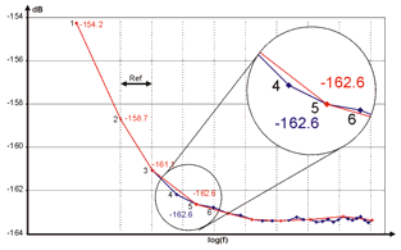
Measure / Stop button:
Start and interrupt the measurement with the this button.

Autorange:
If selected, the autoranging will only be performed once before measuring.

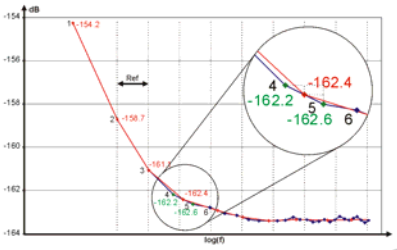
Setup file:
If you push this **Edit button** the SystemSetup file will open. The File contains GPIB commands for the SR770 (refer manual chapter 6) to put the instrument in the setup state. This state is usually used before starting measurement to control and arrange the setup. You can adjust this file by adding or deleting commands. The commands are executed if the **Setup system button** is pressed.



The SR770 can only measure at equidistant frequencies on a linear scale. The data is normally displayed with a logarithmic frequency axis. To reduce the overhead of information in the upper frequency range, the measurement values are converted to an equidistant logarithmic frequency scale, beginning at the indicated sample position.
The start sample positions 2, 5, 10, 20, 30, 50, 100, 200, 300, and 400 can be selected
The two pictures beside show examples for the third sample as start sample.



If averaging is selected, the algorithm to reduce the number of measurement points calculates the mean of all samples until the last taken point and adjusts the frequency to the one in the middle between the last and the current taken frequency. The right picture shows the original (blue) and the converted sequence (red) with averaging. If no averaging is selected only the value at the taken frequency is chosen and the other values are discarded. The left picture shows the original (blue) and the converted sequence (red) without averaging.



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E.4 Program Code

The main source code can be found in the following subchapters.

E.4.1 Header file: FlickerNoiseMeasurement.h

```
// FlickerNoiseMeasurement.h : main header file for the FLICKERNOISEMEASUREMENT application
//

#if !defined(AFX_FLICKERNOISEMEASUREMENT_H__FF726924_2E4B_11D4_B354_0006295283FA__INCLUDED_)
#define AFX_FLICKERNOISEMEASUREMENT_H__FF726924_2E4B_11D4_B354_0006295283FA__INCLUDED_

#if _MSC_VER > 1000
#pragma once
#endif // _MSC_VER > 1000

#ifndef __AFXWIN_H__
  #error include 'stdafx.h' before including this file for PCH
#endif

#include "resource.h"   // main symbols
#include "Decl-32.h"

/////////////////////////////////////////////////////////////////////////////
// CFlickerNoiseMeasurementApp:
// See FlickerNoiseMeasurement.cpp for the implementation of this class
//

class CFlickerNoiseMeasurementApp : public CWinApp
{
public:
  CFlickerNoiseMeasurementApp();

// Overrides
  // ClassWizard generated virtual function overrides
  //{{AFX_VIRTUAL(CFlickerNoiseMeasurementApp)
  public:
  virtual BOOL InitInstance();
  //}}AFX_VIRTUAL

// Implementation

  //{{AFX_MSG(CFlickerNoiseMeasurementApp)
    // NOTE - the ClassWizard will add and remove member functions here.
    //    DO NOT EDIT what you see in these blocks of generated code !
  //}}AFX_MSG
  DECLARE_MESSAGE_MAP()
};


/////////////////////////////////////////////////////////////////////////////

//{{AFX_INSERT_LOCATION}}
// Microsoft Visual C++ will insert additional declarations immediately before the previous line.

#endif // !defined(AFX_FLICKERNOISEMEASUREMENT_H__FF726924_2E4B_11D4_B354_0006295283FA__INCLUDED_)
```

E.4.2 Header file: FlickerNoiseMeasurementDlg.h

```
// FlickerNoiseMeasurementDlg.h : header file
//

#if !defined(AFX_FLICKERNOISEMEASUREMENTDLG_H__FF726926_2E4B_11D4_B354_0006295283FA__INCLUDED_)
#define AFX_FLICKERNOISEMEASUREMENTDLG_H__FF726926_2E4B_11D4_B354_0006295283FA__INCLUDED_

#if _MSC_VER > 1000
#pragma once
#endif // _MSC_VER > 1000

#define DATA_TO_DIALOG FALSE
#define DIALOG_TO_DATA TRUE

const WM_DISPLAY_STATUS    = WM_USER + 100; //benutzerdefinierte Nachricht
const WM_SAVE_DATA     = WM_USER + 101; //benutzerdefinierte Nachricht
const WM_MEASUREMENT_STOPED = WM_USER + 102; //benutzerdefinierte Nachricht
const WM_START_COUNTDOWN= WM_USER + 103; //benutzerdefinierte Nachricht

UINT MeasureThread(LPVOID pParam); //Thread is globally defined!
/////////////////////////////////////////////////////////////////////////////
// CFlickerNoiseMeasurementDlg dialog

class CAveragingRangeType
{
public:
  double Frequency;
  int Averaging;
};

class CFlickerNoiseMeasurementDlg : public CDialog
{
// Construction
public:
```

```
  int CalculateMeasurementTime();
  void CorrectTimeFormat(char *Element);
  void ConvertToMinutesAndSeconds(int *Seconds, int *Minutes);
  int m_SecondsCounter;
  void CountDownSeconds(int Seconds);
  bool PollForSettlingCompletion(CFlickerNoiseMeasurementDlg* pApp, int Span);
  char m_FileNameRaw[200];
  int m_ComboRefStartValue;
  void SetDlgControlState(bool DisableFlag);
  HWND m_hWnd;
  int m_DataTransferTime;
  bool CreateInitInstrumentStandardFile(FILE* Handle);
  bool CreateSystemSetupStandardFile(FILE* Handle);
  bool CreateAveragingRangesStandardFile(FILE* Handle);
//CWinThread* m_MeasureThread;
  bool InstrumentInitialized;
  int CalculateAveraging(double Start, double Stop, double Factor);
// standard constructor
  CFlickerNoiseMeasurementDlg(CWnd* pParent = NULL);
// functions prototypes
  voidSetStandardVariableValues();
  boolCalculateAveragingRanges();
  boolCheckVariableRanges();
  boolInstrumentActive(char *IdentificationString);
  boolGetAveragingRangeEntry(char* Line, double *Frequency, int * Averaging);
  int   GetNumberOfLinesInFile(FILE *Handle);
  boolGetAveragingRangesFromFile();
  int   GetFrequencySpan(double StartFrequency, double StopFrequency);
  voidGetLastVariableSettingsFromFile();
  boolGetMeasurementData(CFlickerNoiseMeasurementDlg* pApp);
  boolProcessData(char *data, double *MeasurementData, int *DataPointer);
  boolPollForCommandCompletion(CFlickerNoiseMeasurementDlg* pApp);
  boolPollForMeasurementCompletion(CFlickerNoiseMeasurementDlg* pApp);
  int   ControlFrequencyRange(double Start, double Stop, double Limit);
  boolReceiveDataSR770(char *data, int count, bool exit, CFlickerNoiseMeasurementDlg* pApp);
  boolSendDataSR770(char *command, CFlickerNoiseMeasurementDlg* pApp);
  boolDisableBoard();
  boolDoMeasurement(double StartFrequency, double StopFrequency, int Averaging, CFlickerNoiseMeasurementDlg* pApp);
  boolInitInstrument();
  voidGPIB_error(char *msg);
  boolFindGBIPCard();
  boolFindInstrument(CString IdentificationString);
  voidDisplayStatus(CString StatusMessage, UINT Type=0);
  voidCalculateCurrentID();
  boolSaveMeasurementDataToFile();
  voidSaveLastVariableSettingsToFile();
  voidpause(long delay);
  boolValidCommand(char* Command);
// Member Variables
  int   m_DataPointerX;
  int   m_DataPointerY;
  double*m_MeasurementDataX;
  double*m_MeasurementDataY;
  charm_FileName[200];
  charm_IdentificationString[50];
  boolm_FirstAverage;
  int   m_NumberOfPassedFrequencyRanges;
  int   m_NumberOfAveragingRanges;
  CAveragingRangeType *m_AveragingRanges;
  int   m_InstrumentHandle;
  int   m_PrimaryInstrumentAddress;
  int   m_SecondaryInstrumentAddress;
  int   m_TimeOut;
  CString m_LastMessage;
  CString m_MessageBoxCaption;
// Dialog Data
  //{{AFX_DATA(CFlickerNoiseMeasurementDlg)
  enum { IDD = IDD_FLICKERNOISEMEASUREMENT_DIALOG };
  CComboBox m_ComboLogSample;
  CStatic m_StatusIcon;
  CButton m_Button_MeasureStop;
  CButton m_Button_EditAvg;
  CComboBox m_Combo_GPIB_Timeout;
  CComboBox m_GPIB_Address;
  CString m_Status;
  doublem_Vr;
  doublem_Vg;
  doublem_Vd;
  doublem_R;
  doublem_P2;
  doublem_P1;
  doublem_FStop;
  doublem_FStart;
  BOOLm_CheckAverage;
  int   m_Radio_AveragingMode;
  BOOLm_CheckLogAverage;
  CString m_TimeToGo;
  //}}AFX_DATA

  // ClassWizard generated virtual function overrides
  //{{AFX_VIRTUAL(CFlickerNoiseMeasurementDlg)
  protected:
  virtual void DoDataExchange(CDataExchange* pDX); // DDX/DDV support
  //}}AFX_VIRTUAL

// Implementation
protected:
  HICON m_hIcon;

  // Generated message map functions
  //{{AFX_MSG(CFlickerNoiseMeasurementDlg)
  virtual BOOL OnInitDialog();
  afx_msg LONG OnStartCountdown(WPARAM Seconds, LPARAM lParam);
  afx_msg LONG OnDisplayStatus(WPARAM Message, LPARAM Status);
  afx_msg LONG OnSaveData(WPARAM wParam, LPARAM lParam);
  afx_msg LONG OnMeasurementStoped(WPARAM wParam, LPARAM lParam);
  afx_msg void OnSysCommand(UINT nID, LPARAM lParam);
  afx_msg void OnPaint();
  afx_msg HCURSOR OnQueryDragIcon();
  afx_msg void OnMeasure();
```

```
  afx_msg void OnKillfocusEditR();
  afx_msg void OnSetfocusEditFstart();
  afx_msg void OnSetfocusEditFstop();
  afx_msg void OnSetfocusEditP1();
  afx_msg void OnSetfocusEditP2();
  afx_msg void OnSetfocusEditR();
  afx_msg void OnSetfocusEditVd();
  afx_msg void OnSetfocusEditVg();
  afx_msg void OnSetfocusEditVr();
  afx_msg void OnFind();
  afx_msg void OnSelchangeComboGpibAddr();
  afx_msg void OnSetupSystem();
  afx_msg void OnButtonEditSetup();
  afx_msg void OnButtonEditInit();
  afx_msg void OnButtonEditAvg();
  afx_msg void OnRadioAvgAuto();
  afx_msg void OnRadioAvgFile();
  afx_msg void OnSetfocusComboGpibAddr();
  afx_msg void OnSetfocusComboGpibTout();
  afx_msg void OnSelchangeComboGpibTimeOut();
  afx_msg void OnKillfocusEdit();
  afx_msg void OnDestroy();
  afx_msg void OnSelchangeComboLogSample();
  afx_msg void OnSetfocusComboLogSample();
  afx_msg void OnTimer(UINT nIDEvent);
  //}}AFX_MSG
  DECLARE_MESSAGE_MAP()
};


//{{AFX_INSERT_LOCATION}}
// Microsoft Visual C++ will insert additional declarations immediately before the previous line.

#endif // !defined(AFX_FLICKERNOISEMEASUREMENTDLG_H__FF726926_2E4B_11D4_B354_0006295283FA__INCLUDED_)
```

E.4.3 Implementation file: FlickerNoiseMeasurement.cpp

```
// FlickerNoiseMeasurement.cpp : Defines the class behaviors for the application.
//

#include "stdafx.h"
#include "FlickerNoiseMeasurement.h"
#include "FlickerNoiseMeasurementDlg.h"

#ifdef _DEBUG
#define new DEBUG_NEW
#undef THIS_FILE
static char THIS_FILE[] = __FILE__;
#endif

/////////////////////////////////////////////////////////////////////////////
// CFlickerNoiseMeasurementApp

BEGIN_MESSAGE_MAP(CFlickerNoiseMeasurementApp, CWinApp)
  //{{AFX_MSG_MAP(CFlickerNoiseMeasurementApp)
    // NOTE - the ClassWizard will add and remove mapping macros here.
    //    DO NOT EDIT what you see in these blocks of generated code!
  //}}AFX_MSG
  ON_COMMAND(ID_HELP, CWinApp::OnHelp)
END_MESSAGE_MAP()

/////////////////////////////////////////////////////////////////////////////
// CFlickerNoiseMeasurementApp construction

CFlickerNoiseMeasurementApp::CFlickerNoiseMeasurementApp()
{
  // TODO: add construction code here,
  // Place all significant initialization in InitInstance
}

/////////////////////////////////////////////////////////////////////////////
// The one and only CFlickerNoiseMeasurementApp object

CFlickerNoiseMeasurementApp theApp;

/////////////////////////////////////////////////////////////////////////////
// CFlickerNoiseMeasurementApp initialization

BOOL CFlickerNoiseMeasurementApp::InitInstance()
{
  AfxEnableControlContainer();

  // Standard initialization
  // If you are not using these features and wish to reduce the size
  //  of your final executable, you should remove from the following
  //  the specific initialization routines you do not need.

#ifdef _AFXDLL
  Enable3dControls();     // Call this when using MFC in a shared DLL
#else
  Enable3dControlsStatic(); // Call this when linking to MFC statically
#endif

  CFlickerNoiseMeasurementDlg dlg;
  m_pMainWnd = &dlg;
  int nResponse = dlg.DoModal();
  if (nResponse == IDOK)
  {
    // TODO: Place code here to handle when the dialog is
    //  dismissed with OK
  }
  else if (nResponse == IDCANCEL)
  {
    // TODO: Place code here to handle when the dialog is
```

```
    //  dismissed with Cancel
  }

  // Since the dialog has been closed, return FALSE so that we exit the
  //  application, rather than start the application's message pump.
  return FALSE;
}
```

E.4.4 Implementation file: FlickerNoiseMeasurementDlg.cpp

```
// FlickerNoiseMeasurementDlg.cpp : implementation file
//

#include "stdafx.h"
#include "FlickerNoiseMeasurement.h"
#include "FlickerNoiseMeasurementDlg.h"
#include <sys\timeb.h> // used in pause()
#include <string.h>
#include <math.h>
#include <process.h>    /* _beginthread, _endthread */


#ifdef _DEBUG
#define new DEBUG_NEW
#undef THIS_FILE
static char THIS_FILE[] = __FILE__;
#endif

#define DISABLED    FALSE
#define ENABLED       TRUE
#define STATUS_INFO     0
#define STATUS_QUESTION   1
#define STATUS_WARNING  2
#define STATUS_ERROR  3
#define STATUS_SUCCESS  4
#define STATUS_MEASURE  5
#define STATUS_TRANS  6
#define STATUS_CARD     7
#define STATUS_FIND     8
#define STATUS_CARD_FIND 9
#define STATUS_SR770  10
#define STATUS_SR770_OK   11
#define STATUS_SAVE     12
#define STATUS_CARD_ERROR 13
#define STATUS_STOPPED  14
#define VERSION_STRING  "V1.4"// Version of parameter file
#define BOARD_INDEX     0   // Board index
#define EOTMODE             1   // Enable the END message
#define EOSMODE             0   // Disable the EOS mode
#define COMMAND             1   // Used for poll function
#define MEASUREMENT         2   // Used for poll function

volatile bool ThreadExitFlag;
char buffer[200];

/////////////////////////////////////////////////////////////////////////////
// CAboutDlg dialog used for App About

class CAboutDlg : public CDialog
{
public:
  CAboutDlg();

  // Dialog Data
  //{{AFX_DATA(CAboutDlg)
  enum { IDD = IDD_ABOUTBOX };
  //}}AFX_DATA

  // ClassWizard generated virtual function overrides
  //{{AFX_VIRTUAL(CAboutDlg)
protected:
  virtual void DoDataExchange(CDataExchange* pDX);    // DDX/DDV support
  //}}AFX_VIRTUAL

  // Implementation
protected:
  //{{AFX_MSG(CAboutDlg)
  //}}AFX_MSG
  DECLARE_MESSAGE_MAP()
};

CAboutDlg::CAboutDlg() : CDialog(CAboutDlg::IDD)
{
  //{{AFX_DATA_INIT(CAboutDlg)
  //}}AFX_DATA_INIT
}

void CAboutDlg::DoDataExchange(CDataExchange* pDX)
{
  CDialog::DoDataExchange(pDX);
  //{{AFX_DATA_MAP(CAboutDlg)
  //}}AFX_DATA_MAP
}

BEGIN_MESSAGE_MAP(CAboutDlg, CDialog)
//{{AFX_MSG_MAP(CAboutDlg)
// No message handlers
//}}AFX_MSG_MAP
END_MESSAGE_MAP()

/////////////////////////////////////////////////////////////////////////////
// CFlickerNoiseMeasurementDlg dialog

CFlickerNoiseMeasurementDlg::CFlickerNoiseMeasurementDlg(CWnd* pParent /*=NULL*/)
```

```
: CDialog(CFlickerNoiseMeasurementDlg::IDD, pParent)
{
  //{{AFX_DATA_INIT(CFlickerNoiseMeasurementDlg)
  m_Status = _T("");
  m_Vr = 0.0;
  m_Vg = 0.0;
  m_Vd = 0.0;
  m_R = 0.0;
  m_P2 = 0.0;
  m_P1 = 0.0;
  m_FStop = 0.0;
  m_FStart = 0.0;
  m_CheckAverage = FALSE;
  m_Radio_AveragingMode = -1;
  m_CheckLogAverage = FALSE;
  m_TimeToGo = _T("");
  //}}AFX_DATA_INIT
  // Note that LoadIcon does not require a subsequent DestroyIcon in Win32
  m_hIcon = AfxGetApp()->LoadIcon(IDR_MAINFRAME);
}

void CFlickerNoiseMeasurementDlg::DoDataExchange(CDataExchange* pDX)
{
  CDialog::DoDataExchange(pDX);
  //{{AFX_DATA_MAP(CFlickerNoiseMeasurementDlg)
  DDX_Control(pDX, IDC_COMBO_LOG_SAMPLE, m_ComboLogSample);
  DDX_Control(pDX, IDC_STATUS_ICON, m_StatusIcon);
  DDX_Control(pDX, IDB_Measure, m_Button_MeasureStop);
  DDX_Control(pDX, IDC_BUTTON_EDIT_AVG, m_Button_EditAvg);
  DDX_Control(pDX, IDC_COMBO_GPIB_TOUT, m_Combo_GPIB_Timeout);
  DDX_Control(pDX, IDC_COMBO_GPIB_ADDR, m_GPIB_Address);
  DDX_Text(pDX, IDC_STATUS, m_Status);
  DDX_Text(pDX, IDC_EDIT_VR, m_Vr);
  DDX_Text(pDX, IDC_EDIT_VG, m_Vg);
  DDX_Text(pDX, IDC_EDIT_VD, m_Vd);
  DDX_Text(pDX, IDC_EDIT_R, m_R);
  DDX_Text(pDX, IDC_EDIT_P2, m_P2);
  DDX_Text(pDX, IDC_EDIT_P1, m_P1);
  DDX_Text(pDX, IDC_EDIT_FSTOP, m_FStop);
  DDX_Text(pDX, IDC_EDIT_FSTART, m_FStart);
  DDX_Check(pDX, IDC_CHECK_AVG, m_CheckAverage);
  DDX_Radio(pDX, IDC_RADIO_AVG_AUTO, m_Radio_AveragingMode);
  DDX_Check(pDX, IDC_CHECK_LOG_AVG, m_CheckLogAverage);
  DDX_Text(pDX, IDC_TIMETOGO, m_TimeToGo);
  //}}AFX_DATA_MAP
}

BEGIN_MESSAGE_MAP(CFlickerNoiseMeasurementDlg, CDialog)
//{{AFX_MSG_MAP(CFlickerNoiseMeasurementDlg)
ON_MESSAGE(WM_START_COUNTDOWN, OnStartCountdown)
ON_MESSAGE(WM_DISPLAY_STATUS, OnDisplayStatus)
ON_MESSAGE(WM_SAVE_DATA, OnSaveData)
ON_MESSAGE(WM_MEASUREMENT_STOPED, OnMeasurementStoped)
ON_WM_SYSCOMMAND()
ON_WM_PAINT()
ON_WM_QUERYDRAGICON()
ON_BN_CLICKED(IDB_Measure, OnMeasure)
ON_EN_KILLFOCUS(IDC_EDIT_R, OnKillfocusEditR)
ON_EN_SETFOCUS(IDC_EDIT_FSTART, OnSetfocusEditFstart)
ON_EN_SETFOCUS(IDC_EDIT_FSTOP, OnSetfocusEditFstop)
ON_EN_SETFOCUS(IDC_EDIT_P1, OnSetfocusEditP1)
ON_EN_SETFOCUS(IDC_EDIT_P2, OnSetfocusEditP2)
ON_EN_SETFOCUS(IDC_EDIT_R, OnSetfocusEditR)
ON_EN_SETFOCUS(IDC_EDIT_VD, OnSetfocusEditVd)
ON_EN_SETFOCUS(IDC_EDIT_VG, OnSetfocusEditVg)
ON_EN_SETFOCUS(IDC_EDIT_VR, OnSetfocusEditVr)
  ON_BN_CLICKED(IDC_Find, OnFind)
  ON_CBN_SELCHANGE(IDC_COMBO_GPIB_ADDR, OnSelchangeComboGpibAddr)
  ON_BN_CLICKED(IDC_SETUP_SYSTEM, OnSetupSystem)
  ON_BN_CLICKED(IDC_BUTTON_EDIT_SETUP, OnButtonEditSetup)
  ON_BN_CLICKED(IDC_BUTTON_EDIT_INIT, OnButtonEditInit)
  ON_BN_CLICKED(IDC_BUTTON_EDIT_AVG, OnButtonEditAvg)
  ON_BN_CLICKED(IDC_RADIO_AVG_AUTO, OnRadioAvgAuto)
  ON_BN_CLICKED(IDC_RADIO_AVG_FILE, OnRadioAvgFile)
  ON_CBN_SETFOCUS(IDC_COMBO_GPIB_ADDR, OnSetfocusComboGpibAddr)
  ON_CBN_SETFOCUS(IDC_COMBO_GPIB_TOUT, OnSetfocusComboGpibTout)
  ON_CBN_SELCHANGE(IDC_COMBO_GPIB_TOUT, OnSelchangeComboGpibTimeOut)
  ON_EN_KILLFOCUS(IDC_EDIT_FSTART, OnKillfocusEdit)
  ON_WM_DESTROY()
  ON_CBN_SELCHANGE(IDC_COMBO_LOG_SAMPLE, OnSelchangeComboLogSample)
  ON_CBN_SETFOCUS(IDC_COMBO_LOG_SAMPLE, OnSetfocusComboLogSample)
ON_EN_KILLFOCUS(IDC_EDIT_VR, OnKillfocusEditR)
ON_EN_KILLFOCUS(IDC_EDIT_VD, OnKillfocusEditR)
  ON_EN_KILLFOCUS(IDC_EDIT_FSTOP, OnKillfocusEdit)
  ON_EN_KILLFOCUS(IDC_EDIT_P1, OnKillfocusEdit)
  ON_EN_KILLFOCUS(IDC_EDIT_P2, OnKillfocusEdit)
  ON_EN_KILLFOCUS(IDC_EDIT_VG, OnKillfocusEdit)
  ON_CBN_KILLFOCUS(IDC_COMBO_GPIB_ADDR, OnKillfocusEdit)
  ON_CBN_KILLFOCUS(IDC_COMBO_GPIB_TOUT, OnKillfocusEdit)
  ON_CBN_KILLFOCUS(IDC_COMBO_LOG_SAMPLE, OnKillfocusEdit)
  ON_WM_TIMER()
  //}}AFX_MSG_MAP
END_MESSAGE_MAP()

/////////////////////////////////////////////////////////////////////////////
// CFlickerNoiseMeasurementDlg message handlers

BOOL CFlickerNoiseMeasurementDlg::OnInitDialog()
{
  CDialog::OnInitDialog();

  // Add "About..." menu item to system menu.

  // IDM_ABOUTBOX must be in the system command range.
  ASSERT((IDM_ABOUTBOX & 0xFFF0) == IDM_ABOUTBOX);
  ASSERT(IDM_ABOUTBOX < 0xF000);

  CMenu* pSysMenu = GetSystemMenu(FALSE);
  if (pSysMenu != NULL)
  {
```

```
    CString strAboutMenu;
    strAboutMenu.LoadString(IDS_ABOUTBOX);
    if (!strAboutMenu.IsEmpty())
    {
      pSysMenu->AppendMenu(MF_SEPARATOR);
      pSysMenu->AppendMenu(MF_STRING, IDM_ABOUTBOX, strAboutMenu);
    }
  }

  // Set the icon for this dialog.  The framework does this automatically
  //  when the application's main window is not a dialog
  SetIcon(m_hIcon, TRUE);     // Set big icon
  //SetIcon(m_hIcon, FALSE);  // Set small icon

  // TODO: Add extra initialization here
  m_TimeToGo = "";
  m_MessageBoxCaption = "Automated Flicker Noise Measurement";
  sprintf(m_IdentificationString, "Stanford_Research_Systems,SR770,s/n24484,ver091");
  GetLastVariableSettingsFromFile();

  if(m_Radio_AveragingMode == 0)m_Button_EditAvg.EnableWindow(FALSE);
  m_GPIB_Address.SetCurSel(m_PrimaryInstrumentAddress-1); //Set GPIB address
  m_Combo_GPIB_Timeout.SetCurSel(m_TimeOut); //Set time out
  m_ComboLogSample.SetCurSel(m_ComboRefStartValue);
  CalculateCurrentID();
  UpdateData(DATA_TO_DIALOG);
  InstrumentInitialized = FALSE;
  return TRUE;  // return TRUE  unless you set the focus to a control
}

void CFlickerNoiseMeasurementDlg::OnSysCommand(UINT nID, LPARAM lParam)
{
  if ((nID & 0xFFF0) == IDM_ABOUTBOX)
  {
    CAboutDlg dlgAbout;
    dlgAbout.DoModal();
  }
  else
  {
    CDialog::OnSysCommand(nID, lParam);
  }
}

// If you add a minimize button to your dialog, you will need the code below
//  to draw the icon.  For MFC applications using the document/view model,
//  this is automatically done for you by the framework.

void CFlickerNoiseMeasurementDlg::OnPaint()
{
  if (IsIconic())
  {
    CPaintDC dc(this); // device context for painting

    SendMessage(WM_ICONERASEBKGND, (WPARAM) dc.GetSafeHdc(), 0);

    // Center icon in client rectangle
    int cxIcon = GetSystemMetrics(SM_CXICON);
    int cyIcon = GetSystemMetrics(SM_CYICON);
    CRect rect;
    GetClientRect(&rect);
    int x = (rect.Width() - cxIcon + 1) / 2;
    int y = (rect.Height() - cyIcon + 1) / 2;

    // Draw the icon
    dc.DrawIcon(x, y, m_hIcon);
  }
  else
  {
    CDialog::OnPaint();
  }
}

// The system calls this to obtain the cursor to display while the user drags
//  the minimized window.
HCURSOR CFlickerNoiseMeasurementDlg::OnQueryDragIcon()
{
  return (HCURSOR) m_hIcon;
}

void CFlickerNoiseMeasurementDlg::GetLastVariableSettingsFromFile()
{
  FILE *Handle;
  char Line[100];
  Handle = fopen( "FNM_LastSettings.txt", "rb" );
  if(Handle == NULL)
  { //no file existe! set options to standard values
    SetStandardVariableValues();
  }
  else
  { //file exists! read lines from file.
    fgets( Line, 100, Handle ); //VERSION_INFO
    if(strncmp(Line, VERSION_STRING, strlen(VERSION_STRING)) == 0)
    {//version identical
      fgets( Line, 100, Handle );//skip file name
      fgets( Line, 100, Handle );
      m_Vg = atof(Line);
      fgets( Line, 100, Handle );
      m_Vd = atof(Line);
      fgets( Line, 100, Handle );
      m_Vr = atof(Line);
      fgets( Line, 100, Handle );
      m_P1= atof(Line);
      fgets( Line, 100, Handle );
      m_R = atof(Line);
      fgets( Line, 100, Handle );
      m_P2 = atof(Line);
      fgets( Line, 100, Handle );
      m_FStart = atof(Line);
      fgets( Line, 100, Handle );
      m_FStop = atof(Line);
```

```
      fgets( Line, 100, Handle );
      m_PrimaryInstrumentAddress = atoi(Line);
      fgets( Line, 100, Handle );
      m_TimeOut = atoi(Line);
      fgets( Line, 100, Handle );
      m_CheckAverage = atoi(Line);
      fgets( Line, 100, Handle );
      m_Radio_AveragingMode = atoi(Line);
      fgets( Line, 100, Handle );
      m_ComboRefStartValue = atoi(Line);
      fgets( Line, 100, Handle );
      m_CheckLogAverage = atoi(Line);
      fclose(Handle);
    }
    else
    {
      MessageBox("Old file version of settings file FNM_LastSettings.txt! \nStandard settings are used!",m_MessageBoxCaption,
MB_OK|MB_ICONWARNING);
      SetStandardVariableValues();
    }
  }
}


void CFlickerNoiseMeasurementDlg::SaveLastVariableSettingsToFile()
{
  FILE *Handle;
  //Generate data file name
  sprintf(m_FileName, "Vd=%2.4fV,Vg=%2.4fV,start=%.2fHz,stop=%.2fHz.txt", m_Vd, m_Vg, m_FStart, m_FStop);        //generate the FilName
  //Generate raw data file name
  sprintf(m_FileNameRaw, "Vd=%2.4fV,Vg=%2.4fV,start=%.2fHz,stop=%.2fHz_raw.txt", m_Vd, m_Vg, m_FStart, m_FStop); //generate the FilName
  Handle = fopen( "FNM_LastSettings.txt", "w" );
  if(Handle == NULL)
  {
    DisplayStatus("Error opening file FNM_LastSettings.txt for writing! Continueing...", STATUS_WARNING);
    pause(1000);
  }
  else
  {
    UpdateData(DIALOG_TO_DATA);
    fprintf(Handle,"%s\n", VERSION_STRING);
    fprintf(Handle,"%s\n",m_FileName);
    fprintf(Handle,"%4.6f\n",m_Vg);
    fprintf(Handle,"%4.6f\n",m_Vd);
    fprintf(Handle,"%4.6f\n",m_Vr);
    fprintf(Handle,"%4.6f\n",m_P1);
    fprintf(Handle,"%4.6f\n",m_R);
    fprintf(Handle,"%4.6f\n",m_P2);
    fprintf(Handle,"%4.6f\n",m_FStart);
    fprintf(Handle,"%4.6f\n",m_FStop);
    fprintf(Handle,"%d\n",m_PrimaryInstrumentAddress);
    fprintf(Handle,"%d\n",m_TimeOut);
    fprintf(Handle,"%d\n",m_CheckAverage);
    fprintf(Handle,"%d\n",m_Radio_AveragingMode);
    fprintf(Handle,"%d\n",m_ComboRefStartValue);
    fprintf(Handle,"%d",m_CheckLogAverage);//Last no carriage return!!!
    fclose(Handle);
  }
}

void CFlickerNoiseMeasurementDlg::CalculateCurrentID()
{
  double dCurrentId;

  if(m_R != 0)
  {
    dCurrentId =  (m_Vr - m_Vd)/m_R;
//  m_Id.Format("ID = %4.2f mA",dCurrentId);
  }
  else
    DisplayStatus("Resistor R = 0 is not allowed!",STATUS_WARNING);
}


void CFlickerNoiseMeasurementDlg::OnKillfocusEditR()
{
  UpdateData(TRUE);
  CalculateCurrentID();
  DisplayStatus("");
}

void CFlickerNoiseMeasurementDlg::DisplayStatus(CString StatusMessage, UINT Type)
{
  UpdateData(DIALOG_TO_DATA); //used, to update changes
  CBitmap StatusIcon;
  if(StatusMessage=="")
  {
    StatusIcon.LoadBitmap(IDB_ICON_EMPTY);
  }
  else
  {
    switch(Type)
    {
    case STATUS_INFO:
      StatusIcon.LoadBitmap(IDB_ICON_INFORMATION);
//    MessageBeep(MB_OK);
      break;
    case STATUS_QUESTION:
      StatusIcon.LoadBitmap(IDB_ICON_QUESTION);
//    MessageBeep(MB_ICONQUESTION);
      break;
    case STATUS_WARNING:
      StatusIcon.LoadBitmap(IDB_ICON_WARNING);
      MessageBeep(MB_ICONEXCLAMATION);
      break;
    case STATUS_ERROR:
      StatusIcon.LoadBitmap(IDB_ICON_ERROR);
      MessageBeep(MB_ICONEXCLAMATION); //MB_ICONHAND
      break;
    case STATUS_SUCCESS:
```

```
      StatusIcon.LoadBitmap(IDB_ICON_SUCCESS);
      MessageBeep(MB_OK);
      break;
    case STATUS_MEASURE:
      StatusIcon.LoadBitmap(IDB_ICON_MEASURE);
//    MessageBeep(MB_OK);
      break;
    case STATUS_TRANS:
      StatusIcon.LoadBitmap(IDB_ICON_TRANS);
//    MessageBeep(MB_OK);
      break;
    case STATUS_CARD:
      StatusIcon.LoadBitmap(IDB_ICON_CARD);
      break;
    case STATUS_CARD_FIND:
      StatusIcon.LoadBitmap(IDB_ICON_CARD_FIND);
      break;
    case STATUS_CARD_ERROR:
      StatusIcon.LoadBitmap(IDB_ICON_CARD_ERROR);
      MessageBeep(MB_ICONEXCLAMATION);
      break;
    case STATUS_SAVE:
      StatusIcon.LoadBitmap(IDB_ICON_SAVE);
      break;
    case STATUS_SR770:
      StatusIcon.LoadBitmap(IDB_ICON_SR770);
//    MessageBeep(MB_OK);
      break;
    case STATUS_SR770_OK:
      StatusIcon.LoadBitmap(IDB_ICON_SR770_OK);
//    MessageBeep(MB_OK);
      break;
    case STATUS_FIND:
      StatusIcon.LoadBitmap(IDB_ICON_FIND);
//    MessageBeep(MB_OK);
      break;
    case STATUS_STOPPED:
      StatusIcon.LoadBitmap(IDB_ICON_STOP);
      MessageBeep(MB_ICONEXCLAMATION);
      break;
    default:
      MessageBox("Wrong argument for function DisplayStatus");
    }
  }
  m_StatusIcon.SetBitmap(HBITMAP(StatusIcon));
//CDialog::OnPaint;
  UpdateWindow();
  //RedrawWindow();
  StatusIcon.Detach();
  m_Status = StatusMessage;
  UpdateData(DATA_TO_DIALOG);
}

void CFlickerNoiseMeasurementDlg::OnSetfocusEditVg()
{
  m_LastMessage = "Please enter the voltage for VG in V.";
  DisplayStatus(m_LastMessage);
}

void CFlickerNoiseMeasurementDlg::OnSetfocusEditVd()
{
  m_LastMessage = "Please enter the voltage for VD in V.";
  DisplayStatus(m_LastMessage);
}

void CFlickerNoiseMeasurementDlg::OnSetfocusEditVr()
{
  m_LastMessage = "Please enter the voltage for VR in V.";
  DisplayStatus(m_LastMessage);
}

void CFlickerNoiseMeasurementDlg::OnSetfocusEditP1()
{
  m_LastMessage = "Please enter the resistor value for the potentiometer P1 in kOhm.";
  DisplayStatus(m_LastMessage);
}

void CFlickerNoiseMeasurementDlg::OnSetfocusEditR()
{
  m_LastMessage = "Please enter the resistor value for the drain resistor R in kOhm.";
  DisplayStatus(m_LastMessage);
}

void CFlickerNoiseMeasurementDlg::OnSetfocusEditP2()
{
  m_LastMessage = "Please enter the resistor value for the potentiometer P2 in kOhm.";
  DisplayStatus(m_LastMessage);
}

void CFlickerNoiseMeasurementDlg::OnSetfocusEditFstart()
{
  m_LastMessage = "Please set the start frequency in Hz. (0 Hz < start < 100000 Hz)";
  DisplayStatus(m_LastMessage);
}

void CFlickerNoiseMeasurementDlg::OnSetfocusEditFstop()
{
  m_LastMessage = "Please set the stop frequency in Hz. (0 Hz < stop <= 100000 Hz)";
  DisplayStatus(m_LastMessage);
}

void CFlickerNoiseMeasurementDlg::OnSetfocusComboGpibAddr()
{
  m_LastMessage = "Please select the GPIB Adress of the SR770. (Standard: 10)";
  DisplayStatus(m_LastMessage);
}

void CFlickerNoiseMeasurementDlg::OnSetfocusComboLogSample()
{
  m_LastMessage = "Please select the start sample for the logarithmic data conversion. (Standard: 20)";
```

```
  DisplayStatus(m_LastMessage);
}

void CFlickerNoiseMeasurementDlg::OnSetfocusComboGpibTout()
{
  m_LastMessage = "Please select the timeout for the SR770. (Standard: 10 s)";
  DisplayStatus(m_LastMessage);
}


void CFlickerNoiseMeasurementDlg::GPIB_error(char *msg)
{
  char str[100];
  char tempbuf[20];

  // Start the Message with the failing GPIB call.
  sprintf(str, msg);

  // Add ibsta information to the Message String.
  strcat(str, "  ibsta = &H");
  itoa(ibsta, tempbuf, 16);
  strcat(str, tempbuf);
  strcat(str, " <");
  if (ibsta & ERR )  strcat(str, " ERR");
  if (ibsta & TIMO)  strcat(str, " TIMO");
  if (ibsta & END )  strcat(str, " END");
  if (ibsta & SRQI)  strcat(str, " SRQI");
  if (ibsta & RQS )  strcat(str, " RQS");
  if (ibsta & CMPL)  strcat(str, " CMPL");
  if (ibsta & LOK )  strcat(str, " LOK");
  if (ibsta & REM )  strcat(str, " REM");
  if (ibsta & CIC )  strcat(str, " CIC");
  if (ibsta & ATN )  strcat(str, " ATN");
  if (ibsta & TACS)  strcat(str, " TACS");
  if (ibsta & LACS)  strcat(str, " LACS");
  if (ibsta & DTAS)  strcat(str, " DTAS");
  if (ibsta & DCAS)  strcat(str, " DCAS");
  strcat(str, " >");

  // Add iberr information to the Message String.
  strcat(str, "\niberr = ");
  itoa(iberr, tempbuf, 10);
  strcat(str, tempbuf);
  if (iberr == EDVR) strcat(str, " EDVR <DOS Error>");
  if (iberr == ECIC) strcat(str, " ECIC <Not CIC>");
  if (iberr == ENOL) strcat(str, " ENOL <No Listener>");
  if (iberr == EADR) strcat(str, " EADR <Address error>");
  if (iberr == EARG) strcat(str, " EARG <Invalid argument>");
  if (iberr == ESAC) strcat(str, " ESAC <Not Sys Ctrlr>");
  if (iberr == EABO) strcat(str, " EABO <Op. aborted>");
  if (iberr == ENEB) strcat(str, " ENEB <No GPIB board>");
  if (iberr == EOIP) strcat(str, " EOIP <Async I/O in prg>");
  if (iberr == ECAP) strcat(str, " ECAP <No capability>");
  if (iberr == EFSO) strcat(str, " EFSO <File sys. error>");
  if (iberr == EBUS) strcat(str, " EBUS <Command error>");
  if (iberr == ESTB) strcat(str, " ESTB <Status byte lost>");
  if (iberr == ESRQ) strcat(str, " ESRQ <SRQ stuck on>");
  if (iberr == ETAB) strcat(str, " ETAB <Table Overflow>");

  // Add ibcntl information to the Message String.
  strcat(str, "\nibcntl = ");
  ultoa(ibcntl, tempbuf, 16);
  strcat(str, tempbuf);
  AfxMessageBox(str, MB_ICONSTOP, 0);

  //  Call the ibonl function to disable the hardware and software.
  ibonl(0, 0);
}

bool CFlickerNoiseMeasurementDlg::FindGBIPCard()
{
  DisplayStatus("Searching GPIB card...", STATUS_CARD_FIND);
  pause(1000);
  SendIFC(0); //at board address 0
  if (ibsta & ERR)
  {
    SetDlgControlState(ENABLED);
    sprintf(buffer, "No GPIB card was found on this computer!");
    DisplayStatus(buffer,STATUS_CARD_ERROR);
    return(FALSE);
  }
  DisplayStatus("GPIB card found!", STATUS_CARD);
  pause(1000);
  return(TRUE);
}


bool CFlickerNoiseMeasurementDlg::InitInstrument()
{
  FILE *Handle;
  char Command[100];

  DisplayStatus("Initializing the instrument...", STATUS_SR770);
  sprintf(Command, "FNM_InstrumentInit.txt");
  Handle = fopen(Command, "rb" );
  if(Handle == NULL)
  { //no file existe! Create file with standard init commands
    Handle = fopen(Command, "w" );
    if(Handle == NULL)
    {
      SetDlgControlState(ENABLED);
      DisplayStatus("Error creating file FNM_SystemSetup.txt! Write protection? Disc space?",STATUS_ERROR);
      return(FALSE);
    }
    CreateInitInstrumentStandardFile(Handle);
    fclose(Handle);
    Handle = fopen(Command, "rb" );
  }
  while(!feof(Handle))
  {
```

```
    fgets(Command, 100, Handle ); //get Command
    if(ValidCommand(Command))
    {
      if(!SendDataSR770(Command, this))
      {
        SetDlgControlState(ENABLED);
        DisplayStatus("ERROR Initializing the SR770!",STATUS_ERROR);
        return(FALSE);
      }
      if(!strncmp(Command,"ARNG1",6))
        pause(5000); //after Autoranging
    }
  }
  DisplayStatus("Instrument initialized!", STATUS_SR770_OK);
  pause(1000);
  return(TRUE);
}

bool CFlickerNoiseMeasurementDlg::SaveMeasurementDataToFile()
{
  int Answer;
  char MessageString[200];
  FILE *Handle1, *Handle2;
  int CurrentRangeINDEX, CurrentValueINDEX, CurrentFrequencyRangeINDEX,CurrentSeriesValueINDEX, FirstRefValue, MeanCounter;
  double LastFrequency, RefFrequencyStep_log, ThisFrequency_log, NextFrequency_log, MeanAccuY, MeanFrequency, LastMeanFrequency;

  DisplayStatus("Storing data...",STATUS_SAVE);
  pause(1000); //to display the information

  //try to open the data file for read to look if file existes
  Handle1 = fopen( m_FileName, "rb" );
  if(Handle1 != NULL)
  {
    fclose(Handle1);
    sprintf(MessageString, "The file %s existes!\nDo you want to overwrite the existing file!", m_FileName);
    Answer = MessageBox(MessageString,m_MessageBoxCaption, MB_OKCANCEL|MB_ICONWARNING);
    if(Answer == 2)//Cancel selected
      return(FALSE);
  }
  do{
    Handle1 = fopen( m_FileName, "w" );
    if(Handle1 == NULL)
    {
      sprintf(MessageString, "Error opening file %s for writing!\nPlease make sure, that file is not opened by another application!", m_FileName);
      Answer = MessageBox(MessageString,m_MessageBoxCaption, MB_RETRYCANCEL|MB_ICONWARNING);
      if(Answer == 2)//Cancel selected
        return(FALSE);
    }
  }while(Handle1 == NULL);

  //try to open the raw data file for read to look if file existes
  Handle2 = fopen( m_FileNameRaw, "rb" );
  if(Handle2 != NULL)
  {
    fclose(Handle2);
    sprintf(MessageString, "The file %s existes!\nDo you want to overwrite the existing file!", m_FileNameRaw);
    Answer = MessageBox(MessageString,m_MessageBoxCaption, MB_OKCANCEL|MB_ICONWARNING);
    if(Answer == 2)//Cancel selected
      return(FALSE);
  }
  do{
    Handle2 = fopen(m_FileNameRaw, "w" );
    if(Handle2 == NULL)
    {
      sprintf(MessageString, "Error opening file %s for writing!\nPlease make sure, that file is not opened by another application!",
m_FileNameRaw);
      Answer = MessageBox(MessageString,m_MessageBoxCaption, MB_RETRYCANCEL|MB_ICONWARNING);
      if(Answer == 2)//Cancel selected
        return(FALSE);
    }
  }while(Handle2 == NULL);

  m_ComboLogSample.GetLBText(m_ComboRefStartValue, buffer);
  FirstRefValue = atoi(buffer)-1;
  LastFrequency = -1; //0Hz can also be for the first value

  //Output all the settings and frequency ranges to the file
  fprintf(Handle1, "VG =\t%6.6f\tVD =\t%6.6f\tVR =\t%6.6f\n", m_Vg, m_Vd, m_Vr);
  fprintf(Handle1, "P1 =\t%6.6f\tR =\t%6.6f\tP2 =\t%6.6f\n", m_P1, m_R, m_P2);
  fprintf(Handle1, "ConvStart =\tsample %d\tAVG =\t%d\n", FirstRefValue+1, m_CheckLogAverage);
  fprintf(Handle1, "FStart =\t%6.6f\tFStop =\t%6.6f\n", m_FStart, m_FStop);
  fprintf(Handle1, "RANGE\tFREQ[Hz]\tAveraging\tRang#=\t%d\n", m_NumberOfAveragingRanges);
  for(CurrentRangeINDEX=0; CurrentRangeINDEX<m_NumberOfAveragingRanges; CurrentRangeINDEX++)
  {
    fprintf(Handle1, "Range%d\t%6.6f\t%d\n", CurrentRangeINDEX+1,
m_AveragingRanges[CurrentRangeINDEX].Frequency,m_AveragingRanges[CurrentRangeINDEX].Averaging);
  }


  //Output the measurement values
  for(CurrentFrequencyRangeINDEX = 0; CurrentFrequencyRangeINDEX < m_NumberOfPassedFrequencyRanges ; CurrentFrequencyRangeINDEX++)
  {
    MeanCounter = 0;
    MeanAccuY = 0;
    for(CurrentSeriesValueINDEX = 0; CurrentSeriesValueINDEX < 400; CurrentSeriesValueINDEX++)
    {
      CurrentValueINDEX = CurrentFrequencyRangeINDEX*400 + CurrentSeriesValueINDEX;
      //output to raw data file (entire samples)
      fprintf(Handle2, "%6.6f\t%6.6f\n", m_MeasurementDataX[CurrentValueINDEX],  m_MeasurementDataY[CurrentValueINDEX]);
      if(m_MeasurementDataX[CurrentValueINDEX]>LastFrequency && m_MeasurementDataX[CurrentValueINDEX]>=0)
      {
        if(CurrentValueINDEX<FirstRefValue)
        {//take the first "FirstRefValue" values and write it to the file
          fprintf(Handle1, "%6.6f\t%6.6f\n", m_MeasurementDataX[CurrentValueINDEX],  m_MeasurementDataY[CurrentValueINDEX]);
          LastFrequency = m_MeasurementDataX[CurrentValueINDEX];
        }
        else
        {
          if(CurrentValueINDEX==FirstRefValue)
          {
```

```
            fprintf(Handle1, "%6.6f\t %6.6f\n", m_MeasurementDataX[CurrentValueINDEX],  m_MeasurementDataY[CurrentValueINDEX]);
            RefFrequencyStep_log = log(m_MeasurementDataX[CurrentValueINDEX]) - log(m_MeasurementDataX[CurrentValueINDEX-1]);
            NextFrequency_log = log(m_MeasurementDataX[CurrentValueINDEX])+RefFrequencyStep_log;
            LastFrequency = m_MeasurementDataX[CurrentValueINDEX];
          }
          else
          {
            ThisFrequency_log = log(m_MeasurementDataX[CurrentValueINDEX]);
            MeanCounter++;
            if(MeanCounter == 1)LastMeanFrequency=m_MeasurementDataX[CurrentValueINDEX];
            MeanAccuY += m_MeasurementDataY[CurrentValueINDEX];
            if(ThisFrequency_log > NextFrequency_log)
            {
              if(m_CheckLogAverage) //take the mean for the last values
              {
                MeanFrequency = LastMeanFrequency + (m_MeasurementDataX[CurrentValueINDEX]-LastMeanFrequency)/2.0;
                fprintf(Handle1, "%6.6f\t %6.6f\n", MeanFrequency,  MeanAccuY/MeanCounter);
              }
              else //take only the value at this frequency
                fprintf(Handle1, "%6.6f\t %6.6f\n", m_MeasurementDataX[CurrentValueINDEX],  m_MeasurementDataY[CurrentValueINDEX]);
              MeanCounter = 0;
              MeanAccuY = 0;
              NextFrequency_log += RefFrequencyStep_log;
              LastFrequency = m_MeasurementDataX[CurrentValueINDEX];
            }
            else
            {
              if(CurrentValueINDEX == ((m_NumberOfPassedFrequencyRanges *400)-1)) //store last value in series
                fprintf(Handle1, "%6.6f\t %6.6f\n", m_MeasurementDataX[CurrentValueINDEX],  m_MeasurementDataY[CurrentValueINDEX]);
            }
          }
        }
      }
    }
  }
  fclose(Handle1);
  fclose(Handle2);
  return(TRUE);
}

bool CFlickerNoiseMeasurementDlg::DisableBoard()
{
  ibonl (BOARD_INDEX, 0);
  SendDataSR770("LOCL0", this); // set to local
  //free allocated memory NOCH: Wieder aktivieren und ueberlegen!
//free(m_MeasurementDataX);
//free(m_MeasurementDataY);
//free(m_AveragingRanges);
  return(TRUE);
}

bool CFlickerNoiseMeasurementDlg::SendDataSR770(char *command, CFlickerNoiseMeasurementDlg* pApp)
{
  char Command[100];
  sprintf(Command,"%s", command);
  strcat(Command, "\n"); //NOCH: Ueberpruefen, ob richtig x0D = 13

  ibwrt (pApp->m_InstrumentHandle, Command, strlen(Command));
  if (ibsta & ERR)
  {
    sprintf(buffer, "Send ERROR! Unrecognized command >>%s<<. Check commands in initialization or system setup file!", command);
    pApp->DisplayStatus(buffer, STATUS_ERROR);
    return(FALSE); //Quit function
  }
  if(!pApp->PollForCommandCompletion(pApp))return(FALSE);
  return(TRUE);
}

bool CFlickerNoiseMeasurementDlg::ReceiveDataSR770(char *data, int count, bool exit, CFlickerNoiseMeasurementDlg* pApp)
{
  ibrd (pApp->m_InstrumentHandle, data, count);
  if ((ibsta & ERR) && exit==TRUE)
  {
    sprintf(data, "Error reading from instrument at address %d!", pApp->m_PrimaryInstrumentAddress);
    ::PostMessage(pApp->m_hWnd, WM_DISPLAY_STATUS, (WPARAM)data, (LPARAM)STATUS_ERROR);
    return(FALSE);
  }
  else
  {
    data[ibcnt-1] = '\0';
  }
  if(!pApp->PollForCommandCompletion(pApp))return(FALSE);
  return(TRUE);
}

int CFlickerNoiseMeasurementDlg::ControlFrequencyRange(double Start, double Stop, double Limit)
{
  if(Start < Limit && Stop <= Limit)
    return(0); //both are in the region
  if(Start < Limit && Stop > Limit)
    return(1); //overlapping
  if(Start >= Limit && Stop > Limit)
    return(2); //not in region
  return(2);
}

void CFlickerNoiseMeasurementDlg::pause(long delay)
{//delay - time to pause in milliseconds
  long stop_ms,ms;
  struct timeb tbuf;

  ftime(&tbuf);
  stop_ms = tbuf.time/1000000;
  stop_ms = tbuf.time - stop_ms * 1000000;
  stop_ms = 1000 * stop_ms + tbuf.millitm + delay;

  do
  {
    ftime(&tbuf);
    ms = tbuf.time/1000000;
```

```
    ms = tbuf.time - ms * 1000000;
    ms = 1000 * ms + tbuf.millitm;
  }
  while (ms < stop_ms);

} /* end pause */

int CFlickerNoiseMeasurementDlg::GetFrequencySpan(double StartFrequency, double StopFrequency)
{
  double FrequencySpan = StopFrequency - StartFrequency;
  if(FrequencySpan < 0.191)
    return(0);
  if(FrequencySpan < 0.382)
    return(1);
  if(FrequencySpan < 0.763)
    return(2);
  if(FrequencySpan < 1.5)
    return(3);
  if(FrequencySpan < 3.1)
    return(4);
  if(FrequencySpan < 6.1)
    return(5);
  if(FrequencySpan < 12.2)
    return(6);
  if(FrequencySpan < 24.4)
    return(7);
  if(FrequencySpan < 48.75)
    return(8);
  if(FrequencySpan < 97.5)
    return(9);
  if(FrequencySpan < 195)
    return(10);
  if(FrequencySpan < 390)
    return(11);
  if(FrequencySpan < 780)
    return(12);
  if(FrequencySpan < 1560)
    return(13);
  if(FrequencySpan < 3125)
    return(14);
  if(FrequencySpan < 6250)
    return(15);
  if(FrequencySpan < 12500)
    return(16);
  if(FrequencySpan < 25000)
    return(17);
  if(FrequencySpan < 50000)
    return(18);
  else
    return(19);
}


bool CFlickerNoiseMeasurementDlg::PollForMeasurementCompletion(CFlickerNoiseMeasurementDlg* pApp)
{
  char serPol;
  int Status;
  //delete the OVERLOAD flag (ignore any previous overloads)
/*ibwrt (m_InstrumentHandle, "ERRE7,0", 7);
  if (ibsta & ERR)
  {
    return(FALSE);
  }
*///start polling
  do
  {
    ibrsp(pApp->m_InstrumentHandle,&serPol);
/*  //Check overload
    ibwrt (m_InstrumentHandle, "ERRS?", 5);
    if (ibsta & ERR)
    {
      return(FALSE);
    }
    ibrd (m_InstrumentHandle, buffer, 100);
    if (ibsta & ERR)
    {
      return(FALSE);
    }
    buffer[ibcnt-1] = '\0';
    Status = atoi(buffer);
  if( Status!=128)
*/

  }while ((serPol&1)==0 && ThreadExitFlag==FALSE); //Frage, ob man das ueberhaupt braucht?
  if(ThreadExitFlag==TRUE)
  {
    ::PostMessage(pApp->m_hWnd, WM_MEASUREMENT_STOPED, 0, 0);
    return(FALSE);
  }
  return(TRUE);
}

bool CFlickerNoiseMeasurementDlg::PollForSettlingCompletion(CFlickerNoiseMeasurementDlg *pApp, int Span)
{
  int Status;
  UINT counter=0;

  do
  {
    ibwrt (m_InstrumentHandle, "FFTS?", 5);
    if (ibsta & ERR)
    {
      return(FALSE);
    }
    ibrd (m_InstrumentHandle, buffer, 100);
    if (ibsta & ERR)
    {
      return(FALSE);
    }
    buffer[ibcnt-1] = '\0';
```

```
    counter++;
    Status = atoi(buffer);
  }while ((counter==1 || Status!=128) && ThreadExitFlag==FALSE && counter<(100000));
  return(TRUE);
}

bool CFlickerNoiseMeasurementDlg::PollForCommandCompletion(CFlickerNoiseMeasurementDlg* pApp)
{
  char serPol;
  do
  {
    ibrsp(pApp->m_InstrumentHandle,&serPol);
  }while ((serPol&2)==0&& ThreadExitFlag==FALSE); //Frage, ob das ueberhaupt gebraucht wird, da der Networkanalyzer sowieso das Flag hochzieht,
nachdem er ein Stopkommando erhalten hat!
  if(ThreadExitFlag==TRUE)
  {
    ::PostMessage(pApp->m_hWnd, WM_MEASUREMENT_STOPED, 0, 0);
    ThreadExitFlag =FALSE;
    return(FALSE);
  }
  return(TRUE);
}

bool CFlickerNoiseMeasurementDlg::GetMeasurementData(CFlickerNoiseMeasurementDlg* pApp)

{
  char dataBuffer[30];
  char Message[200];
  int CurrentValueINDEX;
  sprintf(Message, "Getting measurement data from SR770...");
  ::PostMessage(pApp->m_hWnd, WM_DISPLAY_STATUS, (WPARAM)Message, (LPARAM)STATUS_TRANS);

  for(CurrentValueINDEX=0;CurrentValueINDEX<400;CurrentValueINDEX++)
  {
    sprintf(dataBuffer, "SPEC?0,%d",CurrentValueINDEX);
    if(!pApp->SendDataSR770(dataBuffer,pApp))return(FALSE);
    if(!pApp->ReceiveDataSR770(dataBuffer, 30, TRUE, pApp))return(FALSE);
    pApp->m_MeasurementDataY[pApp->m_DataPointerY] = atof(dataBuffer);
    pApp->m_DataPointerY++;
  }

  for(CurrentValueINDEX=0;CurrentValueINDEX<400;CurrentValueINDEX++)
  {
    sprintf(dataBuffer, "BVAL?0,%d",CurrentValueINDEX);
    if(!pApp->SendDataSR770(dataBuffer,pApp))return(FALSE);
    if(!pApp->ReceiveDataSR770(dataBuffer, 30, TRUE,pApp))return(FALSE);
    pApp->m_MeasurementDataX[pApp->m_DataPointerX] = atof(dataBuffer);
    pApp->m_DataPointerX++;
  }
  return(TRUE);
}

bool CFlickerNoiseMeasurementDlg::GetAveragingRangesFromFile()
{
  FILE *Handle;
  char Line[100];
  int CurrentLimitINDEX;

  Handle = fopen( "FNM_AveragingRanges.txt", "rb" );
  if(Handle == NULL)
  { //no file existe! set options to standard values
    Handle = fopen("FNM_AveragingRanges.txt", "w" );
    if(Handle == NULL)
    {
      SetDlgControlState(ENABLED);
      DisplayStatus("Error creating file FNM_AveragingRanges.txt! Write protection? Disc space?", STATUS_ERROR);
      return(FALSE);
    }
    CreateAveragingRangesStandardFile(Handle);
    fclose(Handle);
    Handle = fopen( "FNM_AveragingRanges.txt", "rb" );
  }
  m_NumberOfAveragingRanges = GetNumberOfLinesInFile(Handle)- 17;
  fclose(Handle);
  Handle = fopen( "FNM_AveragingRanges.txt", "rb" );
  m_AveragingRanges = (CAveragingRangeType*)calloc((unsigned)m_NumberOfAveragingRanges, sizeof(CAveragingRangeType));
  for(CurrentLimitINDEX = 0; CurrentLimitINDEX < 17; CurrentLimitINDEX++)
    fgets( Line, 100, Handle ); //skip line (used for comments)
  for(CurrentLimitINDEX = 0; CurrentLimitINDEX < m_NumberOfAveragingRanges; CurrentLimitINDEX++)
  {
    fgets( Line, 100, Handle );
    GetAveragingRangeEntry(Line, &m_AveragingRanges[CurrentLimitINDEX].Frequency, &m_AveragingRanges[CurrentLimitINDEX].Averaging);
  }
  if(m_AveragingRanges[CurrentLimitINDEX-1].Frequency!=100000)
    m_AveragingRanges[CurrentLimitINDEX-1].Frequency = 100000; //Last frequency has to be 100000
  fclose(Handle);
  return(TRUE);
}

int CFlickerNoiseMeasurementDlg::GetNumberOfLinesInFile(FILE *Handle)
{
  char Line[100], LastLine[100];
  FILE *BufferHandle;
  BufferHandle = Handle;
  int LineCounter = 0;

  while(!feof(Handle))
  {
    fgets( Line, 100, Handle );
    if(strncmp(Line,LastLine,strlen(Line)))
    {
      if(ValidCommand(Line))
        LineCounter++;
    }
    strcpy(LastLine,Line);
  }
  Handle = BufferHandle;
  return(LineCounter);
}
```

```
bool CFlickerNoiseMeasurementDlg::GetAveragingRangeEntry(char *Line, double *Frequency, int *Averaging)
{
  char *Search, *Search2;
  Search = Line;
  Search2 = Search;

  while(*Search2 != ',' && *Search2 != 0 ) Search2++;
  *Search2 = 0;
  *Frequency= atof(Search);
  Search = ++Search2;
  while(*Search2 != 0 ) Search2++;
  *Search2 = 0;
  *Averaging= atoi(Search);
  return(TRUE);
}

void CFlickerNoiseMeasurementDlg::OnFind()
{
  int loop, num_listeners, pad, sad, Dev;
  Addr4882_t instruments[32], result[31];
  char Message[100];

  if(!FindGBIPCard()) return;
  DisplayStatus("Searching for SR770 on GPIB bus...", STATUS_FIND);
  pause(1000);
  for (loop = 0; loop <= 30; loop++)
  {
    instruments[loop] = (Addr4882_t)loop;
  }
  instruments[31] = NOADDR;

  FindLstn(0, &instruments[1], (Addr4882_t *)result, 31);
  if (ibsta & ERR)
  {
    DisplayStatus("ERROR finding SR770. No instruments found on the bus! Connected to bus?", STATUS_ERROR);
    return;
  }

  num_listeners = ibcnt;

  for (loop = 0; loop < num_listeners; loop++)
  {
    pad = GetPAD(result[loop]);
    sad = GetSAD(result[loop]);
    sprintf(Message, "Trying to query instrument at address %d...", pad);
    DisplayStatus(Message, STATUS_SR770);// Normally replaced quickly by following messages
    pause(1000);
    Dev = ibdev(BOARD_INDEX, pad, sad, 13, EOTMODE, EOSMODE);
    if(!(ibsta & ERR))
    {//no error occured
      ibclr(Dev);                /* Clear the device                        */
      if(!(ibsta & ERR))
      {//no error clearing the device
        sprintf(Message, "Trying to get identification string from instrument at address %d...", pad);
        DisplayStatus(Message, STATUS_SR770);// Normally replaced quickly by following messages
        ibwrt (Dev, "*IDN?\n", 7L);
        if(!(ibsta & ERR))
        {//no error sending identification string
          ibrd (Dev, buffer, 100);
          if(!(ibsta & ERR))
          {//no error getting identification string
            buffer[ibcnt-1] = '\0'; //eliminate the carriage return (Asc: 10)
            if (strncmp(buffer, m_IdentificationString, strlen(m_IdentificationString)) == 0)
            {
              sprintf(buffer,"SR770 found at address %d!",pad);
              DisplayStatus(buffer, STATUS_SR770_OK);
              m_PrimaryInstrumentAddress = (Addr4882_t)pad; //Init the Instrument address
              m_SecondaryInstrumentAddress = (Addr4882_t)sad;
              m_InstrumentHandle = Dev;
              m_GPIB_Address.SetCurSel(m_PrimaryInstrumentAddress-1);
              UpdateData(DATA_TO_DIALOG);
              break; //quit the for loop
            }
          }
        }
      }
    }
  }      /*  End of FOR loop */
    if (loop >= num_listeners)
    {
    DisplayStatus("The FFT Network Analyzer SR770 has not been found! \nPlease make sure, that the device is powered on and is properly connected
to the GPIB bus.", STATUS_ERROR);
    return;
  }
}

void CFlickerNoiseMeasurementDlg::OnSelchangeComboGpibAddr()
{
  m_PrimaryInstrumentAddress = m_GPIB_Address.GetCurSel()+1;
}

bool CFlickerNoiseMeasurementDlg::InstrumentActive(char *IdentificationString)
{
  int Dev, pad, sad;

  DisplayStatus("Searching for SR770 on GPIB bus...", STATUS_FIND);
  pause(1000);

  pad = GetPAD(m_PrimaryInstrumentAddress);
  sad = GetSAD(m_PrimaryInstrumentAddress);
  Dev = ibdev(BOARD_INDEX, pad, sad, m_TimeOut, EOTMODE, EOSMODE);
  if (ibsta & ERR)
  {
    SetDlgControlState(ENABLED);
    sprintf(buffer, "Unable to open device SR770 at address %d!", m_PrimaryInstrumentAddress);
    DisplayStatus(buffer, STATUS_ERROR);
    ibonl(0, 0); //free GPIB card
    return FALSE;
  }
```

```
  ibclr(Dev);                /* Clear the device                        */
  if (ibsta & ERR)
  {
    SetDlgControlState(ENABLED);
    sprintf(buffer, "Unable to clear device SR770 at address %d!", m_PrimaryInstrumentAddress);
    DisplayStatus(buffer, STATUS_ERROR);
    ibonl(0, 0); //free GPIB card
    return FALSE;
  }

    ibwrt (Dev, "*IDN?\n", 7L);
  if (ibsta & ERR)
  {
    SetDlgControlState(ENABLED);
    DisplayStatus("ERROR! SR770 turned on? Connected to GPIB bus? Time out? Address?", STATUS_ERROR);
    ibonl(0, 0); //free GPIB card
    return FALSE;
  }

  ibrd (Dev, buffer, 100);
  if (ibsta & ERR)
  {
    SetDlgControlState(ENABLED);
    DisplayStatus("ERROR! SR770 turned on? Connected to GPIB bus? Time out? Address?", STATUS_ERROR);
    ibonl(0, 0); //free GPIB card
    return FALSE;
  }
  buffer[ibcnt-1] = '\0';

  if (strncmp(buffer, IdentificationString, strlen(IdentificationString)) == 0)
  {
    sprintf(buffer,"SR770 found at address %d!",pad);
    DisplayStatus(buffer, STATUS_SR770_OK);
    pause(1000);
    m_InstrumentHandle = Dev;
    m_PrimaryInstrumentAddress = (Addr4882_t)pad;
    m_SecondaryInstrumentAddress = (Addr4882_t)sad;
    return(TRUE);
  }
  SetDlgControlState(ENABLED);
  sprintf(buffer, "SR770 not found at address %d! Use Find... to search for the instrument!", m_PrimaryInstrumentAddress);
  DisplayStatus(buffer, STATUS_ERROR);
  return(FALSE);
}

void CFlickerNoiseMeasurementDlg::OnSetupSystem()
{
  FILE *Handle;
  char Command[100];
  int AveragingFlag;

  if(!FindGBIPCard()) return;
  if(!InstrumentActive(m_IdentificationString)) return;
  if(!InitInstrument()) return;
  DisplayStatus("Prepare instrument for setup...", STATUS_SR770);
  sprintf(Command, "FNM_SystemSetup.txt");
  Handle = fopen(Command, "rb" );
  if(Handle == NULL)
  { //no file existe! Create file with standard init commands
    Handle = fopen(Command, "w" );
    if(Handle == NULL)
    {
      SetDlgControlState(ENABLED);
      DisplayStatus("Error creating file FNM_SystemSetup.txt! Write protection? Disc space?", STATUS_ERROR);
      return;
    }
    CreateSystemSetupStandardFile(Handle);
    fclose(Handle);
    Handle = fopen(Command, "rb" );
  }
  if(!SendDataSR770("ALRM0", this))return; //disable sound
  while(!feof(Handle))
  {
    fgets(Command, 100, Handle ); //get Command
    if(ValidCommand(Command))
    {
      if(!SendDataSR770(Command, this))
      {
        DisplayStatus("ERROR preparing the SR770 for Setup!!", STATUS_ERROR);
        return;
      }
      if(!strncmp(Command,"ARNG1",6))
      {
        // BEGIN
        if(!SendDataSR770("AVGO?", this))return; //Query Averaging
        if(!ReceiveDataSR770(Command, 30, TRUE, this))return; //Get result for Averaging
        AveragingFlag = atoi(Command);
        if(!SendDataSR770("AVGO0", this))return; //Averaging OFF
        if(!SendDataSR770("STRT", this))return;  //Start measurement
        if(!SendDataSR770("ARNG1", this))return; //Auto ranging on
        pause(5000);
        if(!SendDataSR770("ARNG0", this))return; //Auto ranging off
        if(!SendDataSR770("STOP", this))return;  //Start measurement
        sprintf(Command, "AVGO%d",AveragingFlag);
        if(!SendDataSR770(Command, this))return; //Set Averaging back to last setting
      }
    }
  }
  DisplayStatus("System is now ready for setup!", STATUS_SR770_OK);
  SendDataSR770("ALRM1", this);
  SendDataSR770("MSGSSYSTEM_READY", this);
}

bool CFlickerNoiseMeasurementDlg::CheckVariableRanges()
{
  double Dummy;
  if(m_FStart<=0)
  {
    SetDlgControlState(ENABLED);
    GetDlgItem(IDC_EDIT_FSTART)->SetFocus();
```

```
    DisplayStatus("Start frequency has to be positive and unequal to unity!",STATUS_WARNING);
    return(FALSE);
  }
  if(m_FStop<=0)
  {
    SetDlgControlState(ENABLED);
    GetDlgItem(IDC_EDIT_FSTOP)->SetFocus();
    DisplayStatus("Stop frequency has to be positive and unequal to unity!",STATUS_WARNING);
    return(FALSE);
  }
  if(m_FStart>100000)
  {
    SetDlgControlState(ENABLED);
    GetDlgItem(IDC_EDIT_FSTART)->SetFocus();
    DisplayStatus("Start frequency has to be below 100000 Hz!",STATUS_WARNING);
    return(FALSE);
  }
  if(m_FStop>100000)
  {
    SetDlgControlState(ENABLED);
    GetDlgItem(IDC_EDIT_FSTOP)->SetFocus();
    DisplayStatus("Stop frequency has to be below 100000 Hz!",STATUS_WARNING);
    return(FALSE);
  }
  if(m_FStart==m_FStop)
  {
    SetDlgControlState(ENABLED);
    GetDlgItem(IDC_EDIT_FSTART)->SetFocus();
    DisplayStatus("Please select different values for start and stop frequency!",STATUS_WARNING);
    return(FALSE);
  }
  if(m_FStop < m_FStart)
  {
    Dummy = m_FStart;
    m_FStart = m_FStop;
    m_FStop = Dummy;
    UpdateData(DATA_TO_DIALOG);
  }
  return(TRUE);
}

void CFlickerNoiseMeasurementDlg::OnButtonEditSetup()
{
  FILE *Handle;
  Handle = fopen("FNM_SystemSetup.txt", "rb" );
  if(Handle == NULL)
  { //no file existe! Create file with standard init commands
    Handle = fopen("FNM_SystemSetup.txt", "w" );
    if(Handle == NULL)return;
    CreateSystemSetupStandardFile(Handle);
    fclose(Handle);
  }
  system("Notepad FNM_SystemSetup.txt"); //NOCH: esgibt noch einen besseren Befehl!
}

void CFlickerNoiseMeasurementDlg::OnButtonEditInit()
{
  FILE *Handle;
  Handle = fopen("FNM_InstrumentInit.txt", "rb" );
  if(Handle == NULL)
  { //no file existe! Create file with standard init commands
    Handle = fopen("FNM_InstrumentInit.txt", "w" );
    if(Handle == NULL)return;
    CreateInitInstrumentStandardFile(Handle);
    fclose(Handle);
  }
  system("Notepad FNM_InstrumentInit.txt"); //NOCH: esgibt noch einen besseren Befehl!
  //tobi = WinExec("C:\windows\Notepad.exe",SW_SHOW);
}

void CFlickerNoiseMeasurementDlg::OnButtonEditAvg()
{
  FILE *Handle;
  Handle = fopen("FNM_AveragingRanges.txt", "rb" );
  if(Handle == NULL)
  { //no file existe! Create file with standard init commands
    Handle = fopen("FNM_AveragingRanges.txt", "w" );
    if(Handle == NULL)return;
    CreateAveragingRangesStandardFile(Handle);
    fclose(Handle);
  }
  system("Notepad FNM_AveragingRanges.txt"); //NOCH: esgibt noch einen besseren Befehl!
}

void CFlickerNoiseMeasurementDlg::OnRadioAvgAuto()
{
  m_Radio_AveragingMode=0; //Auto mode for averaging
  m_Button_EditAvg.EnableWindow(FALSE);
}

void CFlickerNoiseMeasurementDlg::OnRadioAvgFile()
{
  m_Radio_AveragingMode=1; //ranges from file for averaging
  m_Button_EditAvg.EnableWindow(TRUE);
}

bool CFlickerNoiseMeasurementDlg::CalculateAveragingRanges()
{
  double FSpan_log, FStart_log, FStop_log, FStep_log, FStart, FStop;
  int CurrentFrequencyINDEX;

  FStart_log = log10(m_FStart);
  FStop_log = log10(m_FStop);
  FSpan_log = FStop_log - FStart_log;
  m_NumberOfAveragingRanges = (int)ceil(FSpan_log);
  m_AveragingRanges = (CAveragingRangeType*)calloc((unsigned)m_NumberOfAveragingRanges, sizeof(CAveragingRangeType));
  if(m_NumberOfAveragingRanges == 0) m_NumberOfAveragingRanges =1;
  FStep_log = FSpan_log/m_NumberOfAveragingRanges;
  FStart = m_FStart;
  for(CurrentFrequencyINDEX = 0; CurrentFrequencyINDEX < m_NumberOfAveragingRanges-1; CurrentFrequencyINDEX++)
```

```
  {
    FStop = pow(10, FStart_log + (CurrentFrequencyINDEX+1) * FStep_log);
    m_AveragingRanges[CurrentFrequencyINDEX].Frequency = FStop;
    m_AveragingRanges[CurrentFrequencyINDEX].Averaging = CalculateAveraging(FStart, FStop, (CurrentFrequencyINDEX+1)*FStep_log);
    FStart = FStop;
  }
  m_AveragingRanges[CurrentFrequencyINDEX].Frequency = m_FStop;
  m_AveragingRanges[CurrentFrequencyINDEX].Averaging = CalculateAveraging(FStart, m_FStop, (CurrentFrequencyINDEX+1)*FStep_log);
  return(TRUE);
}

void CFlickerNoiseMeasurementDlg::SetStandardVariableValues()
{
  m_Vg = -1; //V
  m_Vd = 3; //V
  m_Vr = 4; //V
  m_P1 = 10; //kOhm
  m_R = 10; //kOhm
  m_P2 = 10; //kOhm
  m_FStart = 100; //Hz
  m_FStop = 3000; //Hz
  m_PrimaryInstrumentAddress = 10; //Standard GPIB address: 10
  m_TimeOut = 13; //Standard: 10s
  m_CheckAverage = FALSE; //
  m_Radio_AveragingMode = 1; //take from file!
  m_CheckLogAverage = 1;
  m_ComboRefStartValue = 4;
}

void CFlickerNoiseMeasurementDlg::OnSelchangeComboLogSample()
{
  m_ComboRefStartValue = m_ComboLogSample.GetCurSel();
}

void CFlickerNoiseMeasurementDlg::OnSelchangeComboGpibTimeOut()
{
  CString SelectedText;
  m_TimeOut = m_Combo_GPIB_Timeout.GetCurSel();
  if(InstrumentInitialized)
  {
    ibtmo (m_InstrumentHandle, m_TimeOut);
    if(!(ibsta & ERR))
    {
      m_Combo_GPIB_Timeout.GetLBText( m_TimeOut, SelectedText);
      sprintf(buffer, "Time out successfully changed to:%s.", SelectedText );
      DisplayStatus(buffer, STATUS_SR770_OK);
    }
    else
    {
      DisplayStatus("ERROR changing time out!", STATUS_ERROR);
    }
  }
}

bool CFlickerNoiseMeasurementDlg::ValidCommand(char* Command)
{
  char *Search, *Search2;

  Search = Command;
  while(*Search <= 32 && *Search != 0) Search++; //skip leading spaces
  Search2 = Search;
  if(*Search == 0) return(FALSE); //Quit, Line is empty!
  while(*Search2 != 0 && *Search2 != 37) Search2++; //Go to the end of the string
  while((*Search2 <= 32 || *Search2 == 37) && Search2 >= Search) Search2--;
  if(Search == Search2) return(FALSE); //
  Search2++;
  *Search2 = 0;
  if(strlen(Search)<=2) return(FALSE); //GPIB commands are longer then 2 letters
  Command = Search;
  return(TRUE);
}

int CFlickerNoiseMeasurementDlg::CalculateAveraging(double Start, double Stop, double Factor)
{
  int Averaging;
  int NumberOfSeconds = 200; //max time to wait for 400 samples
  Averaging = (int)ceil((NumberOfSeconds/Factor*(Stop - Start)/400));
  return(Averaging);
}

void CFlickerNoiseMeasurementDlg::OnKillfocusEdit()
{
  UpdateData(DIALOG_TO_DATA); //keep database consistent
  DisplayStatus("");
}

bool CFlickerNoiseMeasurementDlg::CreateAveragingRangesStandardFile(FILE* Handle)
{
  fprintf(Handle,"This File is used to set the averaging for different frequency ranges.\n");
  fprintf(Handle,"You can erase or add ranges manually, but always sort in increasing\n");
  fprintf(Handle,"order of frequencies and use the following format:\n");
  fprintf(Handle,"FREQUENCY, AVERAGING\n");
  fprintf(Handle,"////////////////////////////////////////////////////////////\n");
  fprintf(Handle,"//                                                        //\n");
  fprintf(Handle,"//  0 Hz < FREQUENCY <= 100000 Hz                         //\n");
  fprintf(Handle,"//  2 <= AVERAGING <= 32000                               //\n");
  fprintf(Handle,"//  The entry indicates, what AVERAGING should be used    //\n");
  fprintf(Handle,"//  below the specified FREQUENCY.                        //\n");
  fprintf(Handle,"//                                                        //\n");
  fprintf(Handle,"//  ©2000 Tobias Werner                                   //\n");
  fprintf(Handle,"//  University of Stuttgart                               //\n");
  fprintf(Handle,"//  GERMANY                                               //\n");
  fprintf(Handle,"//                                                        //\n");
  fprintf(Handle,"////////////////////////////////////////////////////////////\n");
  fprintf(Handle,"================== Frequency list ========================\n");
  fprintf(Handle,"100, 50\n");
  fprintf(Handle,"3000, 200\n");
  fprintf(Handle,"100000, 500");
  return(TRUE);
}
```

```
bool CFlickerNoiseMeasurementDlg::CreateSystemSetupStandardFile(FILE* Handle)
{
  fprintf(Handle,"SPAN14\t%%span 3.125kHz\n");
  fprintf(Handle,"STRF100\t%%start frequency 100Hz\n");
  fprintf(Handle,"OVLP0\t%%overlapping 0 pecent\n");
  fprintf(Handle,"NAVG200\t%%number of averages 200\n");
  fprintf(Handle,"AVGO1\t%%averaging on\n");
  fprintf(Handle,"ARNG1\t%%autoranging on\n");
  fprintf(Handle,"ARNG0\t%%autoranging off\n");
  fprintf(Handle,"AOFF\t%%perform offset calibration\n");
  fprintf(Handle,"AUTS0\t%%auto scale");
  //Last command no carriage return
  return(TRUE);
}

bool CFlickerNoiseMeasurementDlg::CreateInitInstrumentStandardFile(FILE* Handle)
{
  fprintf(Handle,"*RST\t%%reset the instrument\n");
  fprintf(Handle,"STOP\t%%stop measurement\n");
  fprintf(Handle,"FMTS1\t%%display dual\n");
  fprintf(Handle,"DISP0,0\t%%display log/mag\n");
  fprintf(Handle,"XAXS0,1\t%%x-axis log\n");
  fprintf(Handle,"MEAS0,1\t%%measurement PSD\n");
  fprintf(Handle,"UNIT0,3\t%%dBVrms\n");
  fprintf(Handle,"WNDO0,2\t%%window function Hanning\n");
  fprintf(Handle,"MRKW0,2\t%%marker spot");
  //last Command no carriage return!
  return(TRUE);
}

//NOCH Diese Funktion wieder loeschen
UINT TestThread(LPVOID pParam)
{
  char Message[100];
  int Nummer=0;
  CFlickerNoiseMeasurementDlg* pApp = (CFlickerNoiseMeasurementDlg*)pParam;
  while (!ThreadExitFlag)
  {
    Nummer++;
    sprintf(Message, "Die Nummer ist: %d", Nummer);
    ::PostMessage(pApp->m_hWnd, WM_DISPLAY_STATUS, (WPARAM)Message, (LPARAM)STATUS_MEASURE);
    pApp->pause(1000);
    if(Nummer == 3) break;
  }
  ::PostMessage(pApp->m_hWnd, WM_MEASUREMENT_STOPED, 0, 0);
  return 0;
}

void CFlickerNoiseMeasurementDlg::OnMeasure()
{
  CString ButtonCaption;

  UpdateData(DIALOG_TO_DATA);
  m_Button_MeasureStop.GetWindowText(ButtonCaption);
  if(ButtonCaption == "&Measure")
  {
    SetDlgControlState(DISABLED);
    if(!CheckVariableRanges()) return;
    if(m_Radio_AveragingMode)
      {if(!GetAveragingRangesFromFile())return;}  //Get the frequency ranges from file
    else
      {if(!CalculateAveragingRanges())return;}    //Get the frequency ranges from file
    SaveLastVariableSettingsToFile(); //Save last used settings to a parameter file
    //CalculateCurrentID(); //NOCH: Wieder irgendwo im Dialog die Variable Id einfuegen!

    if(!FindGBIPCard()) return;
    if(!InstrumentActive(m_IdentificationString)) return;
    if(!InitInstrument()) return;
    ThreadExitFlag = FALSE;
    GetDlgItem(IDB_Measure)->EnableWindow(ENABLED);
    m_hWnd = GetSafeHwnd(); //Save window handle in member variable
    CountDownSeconds(CalculateMeasurementTime());
    AfxBeginThread(MeasureThread,(LPVOID)this,THREAD_PRIORITY_NORMAL);
  }
  else //Button caption Stop
  {
    DisplayStatus("Terminating the measurement process. Please wait...", STATUS_STOPPED);
    GetDlgItem(IDB_Measure)->EnableWindow(DISABLED);
    CountDownSeconds(0);
    SendDataSR770("STCO", this); //Stop measurement
    ThreadExitFlag = TRUE; //Exit measurement //NOCH: Reihenfolge veraendert nochmal ueberdenken!
  }
}

UINT MeasureThread(LPVOID pParam)
{
  CFlickerNoiseMeasurementDlg* pApp = (CFlickerNoiseMeasurementDlg*)pParam;
  double Start, Stop;
  bool ExitFlag = FALSE;
  int CurrentLimitINDEX;
  char Message[200];

  pApp->m_NumberOfPassedFrequencyRanges = 0;
  pApp->m_MeasurementDataX = (double*)calloc((unsigned)pApp->m_NumberOfAveragingRanges*400, sizeof(double));
  pApp->m_MeasurementDataY = (double*)calloc((unsigned)pApp->m_NumberOfAveragingRanges*400, sizeof(double));

  Start = pApp->m_FStart;
  Stop = pApp->m_FStop;
  pApp->m_DataPointerX = 0;
  pApp->m_DataPointerY = 0;
  pApp->m_FirstAverage = TRUE;

  sprintf(Message, "Performing auto offset calibration...");
  ::PostMessage(pApp->m_hWnd, WM_DISPLAY_STATUS, (WPARAM)Message, (LPARAM)STATUS_SR770);
//::PostMessage(pApp->m_hWnd, WM_START_COUNTDOWN, (WPARAM)16, 0);
  if(!pApp->SendDataSR770("ALRM0", pApp))return(0); //disable sound
  if(!pApp->SendDataSR770("AOFF", pApp))return(0); //performe auto offset calibration
  if(!pApp->SendDataSR770("AOFM0", pApp))return(0); //disable auto offset
```

```
  for(CurrentLimitINDEX = 0; CurrentLimitINDEX < pApp->m_NumberOfAveragingRanges && ExitFlag == FALSE; CurrentLimitINDEX++)
  {
    switch(pApp->ControlFrequencyRange(Start, Stop, pApp->m_AveragingRanges[CurrentLimitINDEX].Frequency))
    {
    case 0: //start and stop are below the frequency limit
      if(!pApp->DoMeasurement(Start,Stop,pApp->m_AveragingRanges[CurrentLimitINDEX].Averaging, pApp))
      {
        sprintf(Message, "Measurement failed!");
        ::PostMessage(pApp->m_hWnd, WM_DISPLAY_STATUS, (WPARAM)Message, (LPARAM)STATUS_ERROR);
        ::PostMessage(pApp->m_hWnd, WM_MEASUREMENT_STOPED, 0, 0);
        return(0);
      }
      ExitFlag = TRUE; //Exit the while loop
      pApp->m_NumberOfPassedFrequencyRanges++;
      break;
    case 1: //only start is below the frequency limit
      if(!pApp->DoMeasurement(Start,pApp->m_AveragingRanges[CurrentLimitINDEX].Frequency,pApp-
>m_AveragingRanges[CurrentLimitINDEX].Averaging,pApp))
      {
        sprintf(Message, "Measurement failed!");
        ::PostMessage(pApp->m_hWnd, WM_DISPLAY_STATUS, (WPARAM)Message, (LPARAM)STATUS_ERROR);
        ::PostMessage(pApp->m_hWnd, WM_MEASUREMENT_STOPED, 0, 0);
        return(0);
      }
      Start = pApp->m_AveragingRanges[CurrentLimitINDEX].Frequency;
      pApp->m_NumberOfPassedFrequencyRanges++;
      break;
    default: //start and stop are above the frequency limit
      break; //do nothing
    };
  }
  ::PostMessage(pApp->m_hWnd, WM_SAVE_DATA, 0, 0); //Call save data
  return(0);//Thread finished successfully
}

bool CFlickerNoiseMeasurementDlg::DoMeasurement(double StartFrequency, double StopFrequency, int Averaging, CFlickerNoiseMeasurementDlg* pApp)
{
  int FrequencySpanIndex, TimeForSettling; // , TimeForMeasurement;
  double FrequencySpan;

  FrequencySpanIndex = pApp->GetFrequencySpan(StartFrequency, StopFrequency);
  sprintf(buffer, "SPAN%d", FrequencySpanIndex); //0..100,000Hz
  if(!pApp->SendDataSR770(buffer, pApp))return(FALSE);

  sprintf(buffer, "STRF%f.2", StartFrequency); //0..100,000Hz
  if(!pApp->SendDataSR770(buffer, pApp))return(FALSE);

  FrequencySpan = 100000/(pow(2,19-FrequencySpanIndex));
  TimeForSettling = (int)(400/FrequencySpan);

  if(TimeForSettling!=0)
  {
    ::PostMessage(pApp->m_hWnd, WM_DISPLAY_STATUS, (WPARAM)"Frequency range set. Waiting for FFT settling to finish...", (LPARAM)STATUS_MEASURE);
//  ::PostMessage(pApp->m_hWnd, WM_START_COUNTDOWN, (WPARAM)TimeForSettling, 0);
    PollForSettlingCompletion(pApp, FrequencySpanIndex);
  }
  //Calculating the measurement time
//TimeForMeasurement = (int)(400/FrequencySpan*Averaging);
//::PostMessage(pApp->m_hWnd, WM_START_COUNTDOWN, (WPARAM)TimeForMeasurement, 0);

  sprintf(buffer, "Measuring from %.0f Hz to %.0f Hz (Average %d) ...",StartFrequency, StopFrequency, Averaging);
  ::PostMessage(pApp->m_hWnd, WM_DISPLAY_STATUS, (WPARAM)buffer, (LPARAM)STATUS_MEASURE);

  if(!pApp->SendDataSR770("AVGO0", pApp))return(FALSE); //Averaging OFF
  if(!pApp->SendDataSR770("STRT", pApp))return(FALSE);  //Start measurement

  if(m_FirstAverage==TRUE)
  {
    if(!SendDataSR770("ARNG1", pApp))return(FALSE); //Auto ranging on
    pause(5000);
    if(!SendDataSR770("ARNG0", pApp))return(FALSE); //Auto ranging off
    if(pApp->m_CheckAverage==TRUE)
    {
      pApp->m_FirstAverage=FALSE;
    }
  }
  if(!pApp->SendDataSR770("STOP", pApp))return(FALSE);  //Stop measurement
  if(!pApp->SendDataSR770("AVGO1", pApp))return(FALSE); //Averaging ON
  sprintf(buffer, "NAVG %d", Averaging); //Set averaging factor
  if(!pApp->SendDataSR770(buffer, pApp))return(FALSE);
  if(!pApp->SendDataSR770("OVLP0", pApp))return(FALSE); //Overlapping = 0
  if(!pApp->SendDataSR770("AUTS0", pApp))return(FALSE); //Auto scale
  if(!pApp->SendDataSR770("STRT", pApp))return(FALSE);  //Start measurement
  if(!pApp->SendDataSR770("AUTS0", pApp))return(FALSE); //Auto scale
  if(!pApp->PollForMeasurementCompletion(pApp))return(FALSE);
  if(!pApp->SendDataSR770("AUTS0", pApp))return(FALSE); //Auto scale
//::PostMessage(pApp->m_hWnd, WM_START_COUNTDOWN, (WPARAM)10, 0);
  if(!pApp->GetMeasurementData(pApp))return(FALSE);
  return(TRUE);
}

LONG CFlickerNoiseMeasurementDlg::OnDisplayStatus(WPARAM Message, LPARAM Status)
{
  DisplayStatus((char*)Message, (UINT)Status);
  return(0);
}

LONG CFlickerNoiseMeasurementDlg::OnSaveData(WPARAM wParam, LPARAM lParam)
{
  if(SaveMeasurementDataToFile())
  {
    SetDlgControlState(ENABLED);
    CountDownSeconds(0);
    DisplayStatus("Measurement finished successfully!", STATUS_SUCCESS);
    SendDataSR770("ALRM1", this);
    SendDataSR770("MSGS(C)TOBIAS_WERNER_2000", this);
  }
  else
  {
    SetDlgControlState(ENABLED);
```

```
    DisplayStatus("Measurement was canceled!", STATUS_STOPPED);
  }
  DisableBoard();
  return(0);
}

LONG CFlickerNoiseMeasurementDlg::OnMeasurementStoped(WPARAM wParam, LPARAM lParam)
{
  SetDlgControlState(ENABLED);
  DisplayStatus("Measurement stopped!", STATUS_STOPPED);
  DisableBoard();
  return(0);
}

void CFlickerNoiseMeasurementDlg::OnDestroy()
{
  CDialog::OnDestroy();
  SendDataSR770("AOFM1", this); //enable auto offset
  SendDataSR770("ALRM1", this);  //enable sound
  KillTimer(ID_TIMER1);
  ThreadExitFlag = TRUE; //Exit measurement
}


void CFlickerNoiseMeasurementDlg::SetDlgControlState(bool DisableFlag)
{
  GetDlgItem(IDC_EDIT_VG)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_EDIT_VD)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_EDIT_VR)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_EDIT_P1)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_EDIT_R)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_EDIT_P2)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_EDIT_FSTART)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_EDIT_FSTOP)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_RADIO_AVG_AUTO)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_RADIO_AVG_FILE)->EnableWindow(DisableFlag);
  if(m_Radio_AveragingMode)
  {
    GetDlgItem(IDC_BUTTON_EDIT_AVG)->EnableWindow(DisableFlag);
  }
  GetDlgItem(IDC_CHECK_LOG_AVG)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_COMBO_LOG_SAMPLE)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_BUTTON_EDIT_INIT)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_BUTTON_EDIT_SETUP)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_CHECK_AVG)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_COMBO_GPIB_ADDR)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_COMBO_GPIB_TOUT)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_SETUP_SYSTEM)->EnableWindow(DisableFlag);
  GetDlgItem(IDC_Find)->EnableWindow(DisableFlag);
  if(DisableFlag)
  {
    m_Button_MeasureStop.SetWindowText("&Measure");
    GetDlgItem(IDB_Measure)->EnableWindow(DisableFlag);
  }
  else
  {
    m_Button_MeasureStop.SetWindowText("&Stop");
    GetDlgItem(IDB_Measure)->EnableWindow(DisableFlag);
  }
}

void CFlickerNoiseMeasurementDlg::OnTimer(UINT nIDEvent)
{
  char sSeconds[2], sMinutes[2];
  CTime curTime = CTime::GetCurrentTime();
  int Minutes, Seconds;

  m_SecondsCounter--;
  Seconds = m_SecondsCounter;
  if(m_SecondsCounter == 0)
  {
    KillTimer(ID_TIMER1);
    m_TimeToGo = "";
  }
  else
  {
    ConvertToMinutesAndSeconds(&Seconds, &Minutes);
    sprintf(sSeconds, "%d", Seconds);
    CorrectTimeFormat(sSeconds);
    sprintf(sMinutes, "%d", Minutes);
    CorrectTimeFormat(sMinutes);
    m_TimeToGo.Format("%s:%s",sMinutes, sSeconds);
  }
  UpdateData(FALSE);
  CDialog::OnTimer(nIDEvent);
}

void CFlickerNoiseMeasurementDlg::CountDownSeconds(int Seconds)
{
  int Minutes=0;
  char sSeconds[2], sMinutes[2];
  if(Seconds!=0)
  {
    KillTimer(ID_TIMER1);
    m_SecondsCounter = Seconds;
    ConvertToMinutesAndSeconds(&Seconds, &Minutes);
    sprintf(sSeconds, "%d", Seconds);
    CorrectTimeFormat(sSeconds);
    sprintf(sMinutes, "%d", Minutes);
    CorrectTimeFormat(sMinutes);
    m_TimeToGo.Format("%s:%s",sMinutes, sSeconds);
    SetTimer(ID_TIMER1, 1000, NULL);
  }
  else
  {
    m_TimeToGo = "";
    KillTimer(ID_TIMER1);
  }
  UpdateData(FALSE);
}
```

```
void CFlickerNoiseMeasurementDlg::ConvertToMinutesAndSeconds(int *Seconds, int *Minutes)
{
  *Minutes=(int)ceil(*Seconds/60);
  *Seconds = *Seconds - (*Minutes*60);
}


void CFlickerNoiseMeasurementDlg::CorrectTimeFormat(char *Element)
{
  char DummyString[2];
  if(strlen(Element)==1)
    sprintf(DummyString, "0%s",Element);
  else
    sprintf(DummyString, "%s",Element);
  strcpy(Element,DummyString);
}

LONG CFlickerNoiseMeasurementDlg::OnStartCountdown(WPARAM Seconds, LPARAM lParam)
{
  CountDownSeconds((int)Seconds);
  return(0);
}

int CFlickerNoiseMeasurementDlg::CalculateMeasurementTime()
{
  int EntireTime, OffsetTime, SettlingTime, MeasurementTime, TransferTime, OverheadTime, AveragingRangeINDEX;
  double Start,Stop,FrequencySpan;
  OffsetTime = 16; //s
  TransferTime = 10; //s
  OverheadTime = 7; //s

  EntireTime = OverheadTime + OffsetTime;

  Start = m_FStart;
  Stop = m_FStop;

  for(AveragingRangeINDEX=0; AveragingRangeINDEX<m_NumberOfAveragingRanges;AveragingRangeINDEX++)
  {
    switch(ControlFrequencyRange(Start, Stop, m_AveragingRanges[AveragingRangeINDEX].Frequency))
    {
    case 0: //start and stop are below the frequency limit
      FrequencySpan = 100000/(pow(2,19-GetFrequencySpan(Start, Stop)));
      SettlingTime = (int)(400/FrequencySpan);
      MeasurementTime = (int)(400/FrequencySpan*m_AveragingRanges[AveragingRangeINDEX].Averaging);
      EntireTime += SettlingTime + MeasurementTime + TransferTime + OverheadTime;
      return(EntireTime);
    case 1: //only start is below the frequency limit
      FrequencySpan = 100000/(pow(2,19-GetFrequencySpan(Start, m_AveragingRanges[AveragingRangeINDEX].Frequency)));
      Start = m_AveragingRanges[AveragingRangeINDEX].Frequency;
      SettlingTime = (int)(400/FrequencySpan);
      MeasurementTime = (int)(400/FrequencySpan*m_AveragingRanges[AveragingRangeINDEX].Averaging);
      EntireTime += SettlingTime + MeasurementTime + TransferTime + OverheadTime;
      break;
    default: //start and stop are above the frequency limit
      break; //do nothing
    };
  }
  return(EntireTime);
}
```

Appendix F: FIXTURE CHARACTERIZATION

In a microwave noise measurement setup, all elements of the system have to be characterized concerning their high frequency properties in order to get accurate results. Vector network analyzers (VNA) are used for this purpose and measure the S-parameters, which describe these properties.

To get accurate measurement results for the S-parameters, the VNA has to be calibrated. A measurement calibration is a process, which mathematically derives the error model for the VNA. This error model is an array of vector coefficients used to establish a fixed reference plane of zero phase shift, zero magnitude and known impedance. The array coefficients are computed by measuring a set of "known" devices, connected at a fixed point and solving the vector difference between the modeled and the measured response. These known devices are called calibration standards and they have a precisely known magnitude and phase response as a function of frequency.

In general a microwave measurement setup consists of devices with the same connector family and insertable connections, i.e. a female contact on one side and a male contact on the other side. In this case it is very easy to measure the S-parameters of this device, because it is the configuration intended for a VNA measurement process. *Fig. F.1* shows an example of an insertable system component.

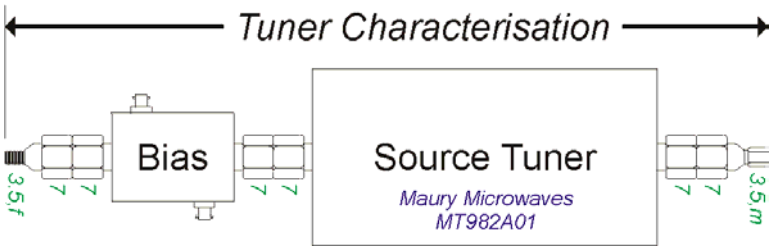


Fig. F.1: Example of an insertable system component with APC3.5 female connectors at the input and APC3.5 male connectors at the output.

If the S-parameters of a non-insertable system component has to be measured the adapter removal technique [35] can be used. *Fig. F.2* shows an example of a non-insertable system component.

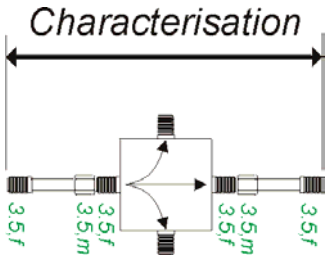
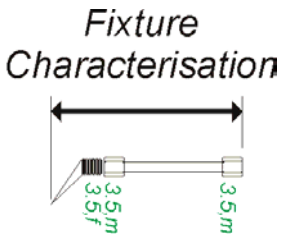


Fig. F.2: Example of a non-insertable system component with APC3.5 female connectors at the input and output.

If even the connector family is different for a device, there is still a way to measure the S-parameters as described in [35].



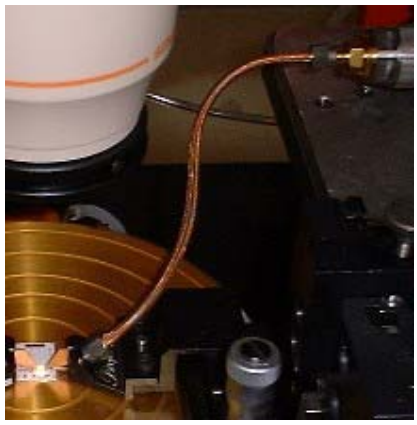


Fig. F.3: Example of a device with an APC3.5 male connector on one side and a connector-less end on the other side.

In our case we had the problem to characterize the high frequency properties of a fixture, consisting of a low loss cable and a microwave probe tip, shown in *Fig. F.3*.

The following chapter describes, how this problem was solved by performing two one port calibrations and applying the two sets of corresponding error terms of the HP8510C to calculate the S-parameters of the fixture.

F.1 Systematic approach

If a one-port calibration is performed, the error coefficients E_R, representing the frequency response, E_D, the directivity and E_S, the source match, are calculated from solving an equation for an open, short and load calibration standard, connected to the reference plane of the VNA [38]. These error coefficients represent the S-parameters of the network between the VNA and the reference plane at which the calibration was carried out. The network is considered passive and reciprocal. *Fig. F.4* shows an illustration of the so-called error adapter calculated from the error coefficients.

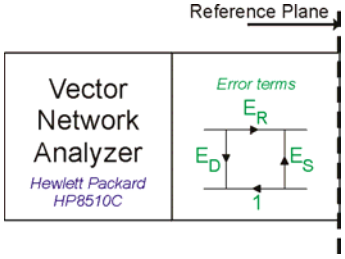


Fig. F.4: The error model for a one-port calibration with the HP8510C.

The error adapter can be described by the S-parameter matrix

$$\mathbf{A}_S = \begin{bmatrix} E_D & 1 \\ E_R & E_S \end{bmatrix}. \tag{F.1}$$

Two calibrations have to be performed to calculate the S-parameters of the fixture. One calibration at the coaxial reference plane with a 3.5 mm calibration kit, the other with the fixture connected at the previous reference plane with an on-waver calibration substrate, like demonstrated on the left and right side of *Fig. F.5*.

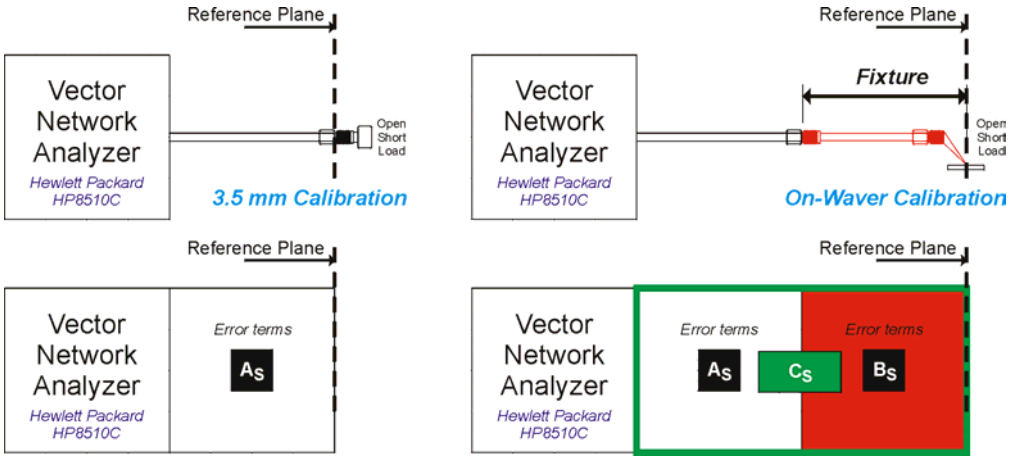


Fig. F.5: The error terms of two one-port calibrations can be used to calculate the S-parameters of the fixture.

For the first calibration we get a set of coefficients expressed by the matrix

$$\mathbf{A}_S = \begin{bmatrix} E_{D1} & 1 \\ E_{R1} & E_{S1} \end{bmatrix}. \tag{F.2}$$

The second set of error coefficients is expressed by the matrix

$$\mathbf{C}_S = \begin{bmatrix} E_{D2} & 1 \\ E_{R2} & E_{S2} \end{bmatrix} \tag{F.3}$$

and consists of the same matrix $\mathbf{A}_S$ as in (F.2) in chain with a matrix $\mathbf{B}_S$ expressing the S-parameters of the fixture.

To calculate the matrix $\mathbf{B}_S$ we transform the two S-parameter matrices $\mathbf{A}_S$ and $\mathbf{C}_S$ into chain matrices $\mathbf{A}_T$ and $\mathbf{C}_T$ by the conversion

$$\begin{aligned} X_{T11} &= X_{S12} - \frac{X_{S11} \cdot X_{S22}}{X_{S21}} \\ X_{T12} &= \frac{X_{S11}}{X_{S21}} \\ X_{T21} &= -\frac{X_{S22}}{X_{S21}} \\ X_{T22} &= \frac{1}{X_{S21}} \end{aligned} \tag{F.4}$$

and get

$$\mathbf{A}_T = \begin{bmatrix} \dfrac{E_{R1}\text{-}E_{D1}\cdot E_{S1}}{E_{R1}} & \dfrac{E_{D1}}{E_{R1}} \\ -\dfrac{E_{S1}}{E_{R1}} & \dfrac{1}{E_{R1}} \end{bmatrix}, \tag{F.5}$$

and

$$\mathbf{C}_T = \begin{bmatrix} \dfrac{E_{R2}\text{-}E_{D2}\cdot E_{S2}}{E_{R2}} & \dfrac{E_{D2}}{E_{R2}} \\ -\dfrac{E_{S2}}{E_{R2}} & \dfrac{1}{E_{R2}} \end{bmatrix}. \tag{F.6}$$

For the chain matrix can be written

$$\mathbf{C}_T = \mathbf{A}_T \cdot \mathbf{B}_T, \tag{F.7}$$

or

$$\mathbf{B}_T = \mathbf{A}_T{}^{-1} \cdot \mathbf{C}_T. \tag{F.8}$$

With (F.5) and (F.6) in (F.8) we get

$$\mathbf{B}_T = \begin{bmatrix} \dfrac{E_{R2}\text{-}E_{D2}\cdot E_{S2}+E_{D1}\cdot E_{S2}}{E_{R2}} & \dfrac{E_{D2}\text{-}E_{D1}}{E_{R2}} \\ \dfrac{E_{S1}\cdot E_{R2}\text{-}E_{S1}\cdot E_{D2}\cdot E_{S2}\text{-}E_{S2}\cdot E_{R1}+E_{S2}\cdot E_{D1}\cdot E_{S1}}{E_{R2}} & \dfrac{E_{S1}\cdot E_{D2}+E_{R1}\text{-}E_{D1}\cdot E_{S1}}{E_{R2}} \end{bmatrix}. \tag{F.9}$$

After converting (F.9) back to S-parameters by the formula

$$\begin{aligned} X_{S11} &= \frac{X_{T12}}{X_{T22}} \\ X_{S12} &= X_{T11} - \frac{X_{T21}\cdot X_{T22}}{X_{T22}} \\ X_{S21} &= \frac{1}{X_{T22}} \\ X_{S22} &= -\frac{X_{T21}}{X_{T22}} \end{aligned} \tag{F.10}$$

and taking into account that S_{12} equals S_{21} for the fixture, we get

$$\mathbf{B}_S = \begin{bmatrix} \dfrac{E_{D2}-E_{D1}}{E_{S1}\cdot E_{D2}+E_{R1}-E_{D1}\cdot E_{S1}} & \pm\sqrt{\dfrac{E_{R1}\cdot E_{R2}}{(E_{S1}\cdot E_{D2}+E_{R1}-E_{D1}\cdot E_{S1})^2}} \\ \pm\sqrt{\dfrac{E_{R1}\cdot E_{R2}}{(E_{S1}\cdot E_{D2}+E_{R1}-E_{D1}\cdot E_{S1})^2}} & \dfrac{-E_{S1}\cdot E_{R2}+E_{S1}\cdot E_{D2}\cdot E_{S2}+E_{S2}\cdot E_{R1}-E_{S2}\cdot E_{D1}\cdot E_{S1}}{E_{S1}\cdot E_{D2}+E_{R1}-E_{D1}\cdot E_{S1}} \end{bmatrix} \tag{F.11}$$

Equation (F.11) represents the S-parameters of the unknown fixture by the error coefficients of two one-port calibrations. As can be seen from this equation, there are two possible solutions for S_{12} and S_{21}, equal in magnitude but 180 degrees apart in phase.

To get the correct physical result, further investigations has to be made and will be discussed in the next chapter.

F.2 Phase ambiguity

For an ideal loss less transmission line the S-parameters are given by

$$\mathbf{D}_S = \begin{bmatrix} 0 & e^{-j\cdot\beta\cdot\ell} \\ e^{-j\cdot\beta\cdot\ell} & 0 \end{bmatrix}, \tag{F.12}$$

with ℓ, the electrical length of the line and β, the phase constant.

From (F.12) follows for the phase φ of S_{12} and S_{21}

$$\varphi = -\beta\cdot\ell, \tag{F.13}$$

with $\beta = \dfrac{2\cdot\pi}{\lambda}$ and the wavelength $\lambda = \dfrac{c}{f}$ in (F.13) the phase will be

$$\varphi(f) = -\frac{2\cdot\pi\cdot\ell}{c}\cdot f\,. \tag{F.14}$$

From (F.14) can be seen that the phase has a linear frequency dependence. The slope *m* of the line is

$$m = -\frac{2\cdot\pi\cdot\ell}{c}\,. \tag{F.15}$$

Fig. F.6 shows the course of $S_{12} = S_{21}$, if only one solution of (F.11) is taken into account. The phase varies between -90 and + 90 degreed and not -180 and +180 as expected.

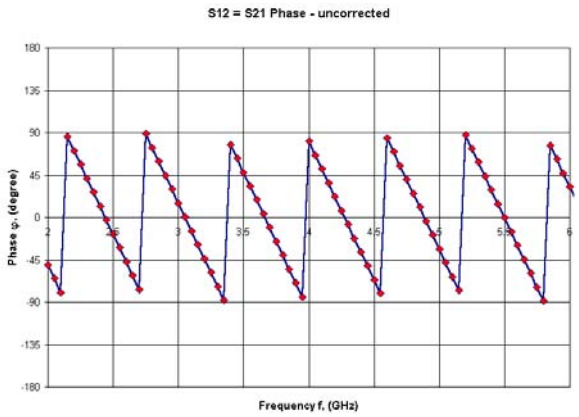


Fig. F.6: Uncorrected phase of S12 and S21.The dots represent the discrete measured values and the line is the linear interpolation between them.

The slope of a line segment can be calculated by taking two discrete points with frequency f and corresponding phase φ:

$$m = \frac{\Delta\varphi}{\Delta f} = \frac{\varphi_2(f_2) - \varphi_1(f_1)}{f_2 - f_1}. \tag{F.16}$$

If we compare (F.15) and (F.16) and solve for the electrical length ℓ, we get

$$\ell = -\frac{c}{2 \cdot \pi} \cdot \frac{\varphi_2(f_2) - \varphi_1(f_1)}{f_2 - f_1}. \tag{F.17}$$

This electrical length ℓ can now be inserted in (F.13) to calculate the theoretical value of the phase at each frequency of S_{12} and S_{21}. Than the theoretical value can be compared to the calculated value of the phase from measurement and can be corrected by 180 degrees if necessary. *Fig. F.7* shows the corrected phase information for S_{12} and S_{21}.

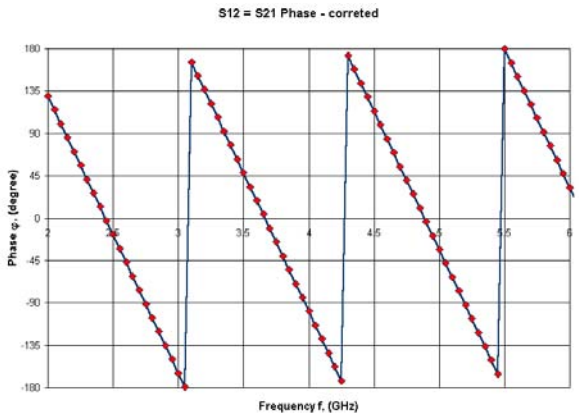


Fig. F.7: Corrected phase of S12 and S21

The algorithm to calculate the electrical length will only work, if the frequency spacing is close enough related to the electrical length of the fixture. *Fig. F.8* shows a good (left) and an unsuitable (right) selection for the frequency spacing.

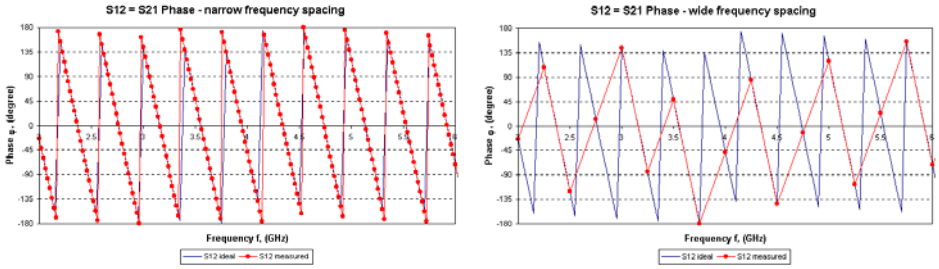

S12 = S21 Phase - narrow frequency spacing
S12 = S21 Phase - wide frequency spacing
Phase φ, (degree)
Frequency f, (GHz)
S12 ideal
S12 measured

Fig. F.8: The slope of the line segment can be easily calculated in the left example, but will lead to a wrong result for the electrical length in the right example.

F.3 Matlab Program

The presented procedure to calculate the S-parameters of a fixture from the error coefficients of two VNA one-port calibrations was implemented in Matlab. The program accepts two standard calibration files of the HP8510C and calculates the S-parameters with corrected phase information for S_{12} and S_{21}. The S-parameters are then written to a file in a touchstone compatible format and can be used to setup the microwave systems.

F.4 Verification of the results

To control that the program is working correctly, the S-parameters of a fixture were calculated by applying the presented algorithm and the result was compared to that of a commercial fixture characterization program (Maury Microwave, MT956 Fixture Software, $3500). The conditions were not exactly the same, because the rigid low loss cable was bended between the two measurements and therefore changed its electrical characteristics slightly. Nevertheless the agreement between these two measurements is very good and shows that the implemented algorithm is working excellent.

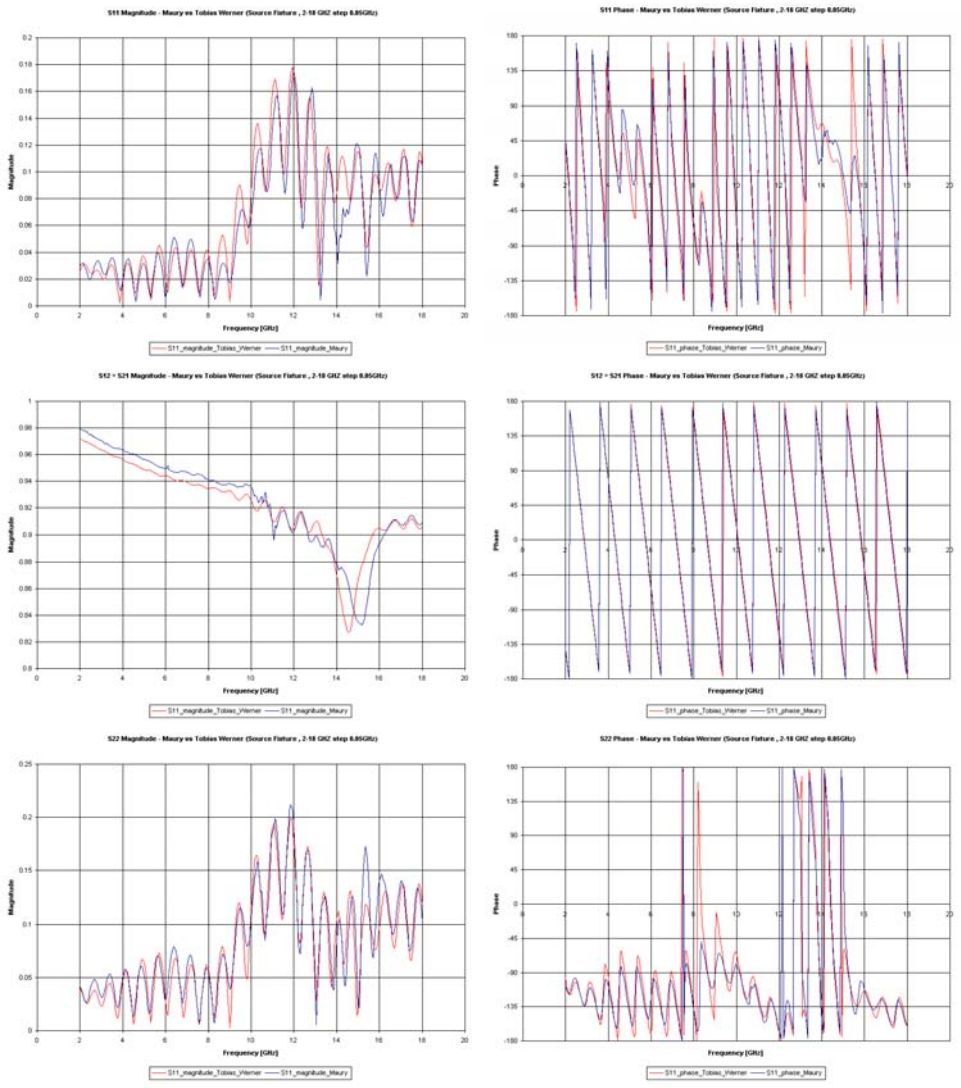


Fig. F.9: Comparison between the results for an S-parameter determination of a commercial system (blue) and the presented Matlab program (red). On the left side is the magnitude and on the right side the phase of the S-parameters.

F.5 Matlab source code

```
function y = CalculateFixture
%   Funktion:     Calculate Fixture
%   Author:       Tobias Werner, Universitaet Stuttgart
%   Date:         Februar 2000
%   DESCRIPTION:
%   ============
%   Function opens two calibration sets of the HP8510C and calculates
%   the S-Parameters of the fixture.

clear all
clc
home
disp('      ')
disp('       F I X T U R E   C A L C U L A T I O N')
disp('       ====================================')
disp(' ____________________________________________________')
disp('|                                                    |')
disp('|    This program calculates the S-parameters of a   |')
disp('|   fixture from two HP8510 error correction terms.  |')
disp('|                                                    |')
disp('|                (c) Februar 2000                    |')
disp('|                  Tobias Werner                     |')
disp('|             University of Stuttgart               |')
disp('|____________________________________________________|')


% ---------Ask for calibration file without fixture to open-------
text = sprintf('\nIn the current directory the following calibration files were found:\n');
disp(text);
eval('ls CS*');

%%%%%%%%%%%%%%% SELECT AND OPEN CALFILE WITHOUT FIXTURE %%%%%%%%%%%%%%%
file_name1 = input('\nPlease select the file, which contains the calibration information WITHOUT FIXTURE:\n[Type the name of the file]  ','s');

% ----------open and control the selected file-------
CalFile1 = fopen(file_name1,'r');
if CalFile1 == -1
  text = sprintf('File %s not found!', file_name1);
  disp(text);
  disp('E X I T  P R O G R A M')
  return;
end
NumberOfErrorTerms1 = CheckFor8510CalibFile(CalFile1);
if NumberOfErrorTerms1 == 0
  fclose(CalFile1)
  return;
end

%%%%%%%%%%%%%%% SELECT AND OPEN CALFILE WITH FIXTURE %%%%%%%%%%%%%%%
file_name2 = file_name1;
while strcmp(file_name1, file_name2)
  file_name2 = input('\nPlease select the file, which contains the calibration information WITH FIXTURE:\n[Type the name of the file]  ','s');
  if strcmp(file_name1, file_name2)
    text = sprintf('\nERROR! You have chosen the same file as before. Try again:');
    disp(text);
  end
end

% ---------open and control the selected file-------
CalFile2 = fopen(file_name2,'r');
if CalFile2 == -1
  text = sprintf('File %s not found!', file_name2);
  disp(text);
  disp('E X I T  P R O G R A M')
  return;
end
NumberOfErrorTerms2 = CheckFor8510CalibFile(CalFile2);
if NumberOfErrorTerms2 == 0
  fclose(CalFile2)
  return;
end

% ---------enter electrical length, if known
Electrical_Length = str2num(input('\nPlease specify the ELECTRICAL LENGTH of the fixture, if known, or press ENTER to let the program calculate it
automatically.\n(NOTE! If the electrical length is calculated by the program, please make sure that the frequency spacing of the two calibration
sets has been chosen small enough! Otherwise, the program will calculate a incorrect value!)\n[Type in the electrical length in m or press ENTER
to continue:] ','s'));

%%%%%%%%%%%%%%%%%% Read the frequencies of both files and compare them %%%%%%%%%%%%%%%%%%
disp(' ')
disp('================ PROCCESSING DATA ================')
disp(' ')
text = sprintf('- Proccessing error correction file WITHOUT FIXTURE (%s):', file_name1);
disp(text)
FrequencyArray1 = ReadFrequencyList(CalFile1);
if FrequencyArray1 == 0
  return
end
NumberOfFrequencies1 = size(FrequencyArray1,1);
text = sprintf('- Proccessing error correction file WITH FIXTURE (%s):', file_name2);
disp(text)
FrequencyArray2 = ReadFrequencyList(CalFile2);
if FrequencyArray2 == 0
  return
end
NumberOfFrequencies2 = size(FrequencyArray2,1);

% Control, if frequency ranges are the same
if FrequencyArray1 ~= FrequencyArray2
```

```
  disp('You have to use the same frequency spacing for the two calibration files!')
  disp('E X I T  P R O G R A M')
  return
end

%%%%%%%%%%%%%%%%%% Read the error terms from the two files %%%%%%%%%%%%%%%%%%
text = sprintf('- Proccessing error correction file WITHOUT FIXTURE (%s):', file_name1);
disp(text)
for CurrentErrorTerm_INDEX1 = 1:NumberOfErrorTerms1
  Buffer = ReadErrorTerms(CalFile1, NumberOfFrequencies1);
  if size(Buffer,1) ~= NumberOfFrequencies1
    disp('ERROR! The number of frequencies differs from the number of error terms!')
    disp('E X I T  P R O G R A M')
    return
  else
    ErrorTermArray1(:,CurrentErrorTerm_INDEX1) = Buffer;
  end
end

text = sprintf('- Proccessing error correction file WITH FIXTURE (%s):', file_name2);
disp(text)
for CurrentErrorTerm_INDEX2 = 1:NumberOfErrorTerms2
  Buffer = ReadErrorTerms(CalFile2, NumberOfFrequencies2);
  if size(Buffer,1) ~= NumberOfFrequencies2
    disp('ERROR! The number of frequencies differs from the number of error terms!')
    disp('E X I T  P R O G R A M')
    return
  else
    ErrorTermArray2(:,CurrentErrorTerm_INDEX2) = Buffer;
  end
end


%%%%%%%%%%%%%%%%%% Calculate the S-parameters for the fixture %%%%%%%%%%%%%%%%%%
Fixture_S_MA = CalculateFixtureSParameter(ErrorTermArray1,ErrorTermArray2, FrequencyArray1, Electrical_Length);

%%%%%%%%%%%%%%%%%% Store the S-parameters for the fixture %%%%%%%%%%%%%%%%%%
if StoreFixtureFile(Fixture_S_MA, file_name1, file_name2)
  return %Error
end

text = sprintf('\nPROGRAMM FINISHED SUCCESSFULLY');
disp(text);

fclose(CalFile1);
fclose(CalFile2);
return


%END OF MAIN PROGRAM

% ========================FUNCTIONS=================================

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FUNCTION: CheckFor8510CalibFile(FileHandler)                                 %
% INPUT:    FileHeandler                                                       %
% OUTPUT:   Number of error terms                                              %
% AUTOR:    Tobias Werner, Universitaet Stuttgart                              %
% DATE:     February 29, 2000                                                  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function y = CheckFor8510CalibFile(CalFile)
  % Look for the word DATA in CalFile
  exit_counter = 1;
  while isempty(findstr(fgetl(CalFile), 'DATA')) & exit_counter < 10
    exit_counter = exit_counter + 1;
  end

  % Count the occurence of the word DATA in CalFile
  DATA_counter = 1;
  while ~isempty(findstr(fgetl(CalFile), 'DATA'))
    DATA_counter = DATA_counter + 1;
  end

  switch DATA_counter
    case 3
      disp('1-PORT HP8510C CALIBRATION FILE: 3 ERROR TERMS FOUND.')
      y = DATA_counter;
    case 12
      disp('ERROR! The algorithm for a 2-Port calibration file is not yet implemented!')
      disp('E X I T  P R O G R A M')
      y = DATA_counter;
    otherwise
      disp('ERROR! The file is not a HP8510C calibration file!')
      disp('E X I T  P R O G R A M')
      y = 0;
  end
return
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FUNCTION: ReadFrequencyList(FileHandler)                                       %
% INPUT:    FileHeandler                                                         %
% OUTPUT:   Vektor (Frequency list read from indicated file)                     %
% AUTOR:    Tobias Werner, Universitaet Stuttgart                                %
% DATE:     February 29, 2000                                                    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function y = ReadFrequencyList(CalFile)
  exit_counter = 1;
  current_String = fgetl(CalFile);
  while isempty(findstr(current_String,'_LIST_'))
    exit_counter = exit_counter + 1;
    if exit_counter > 19
      disp('ERROR in file format!')
      disp('E X I T  P R O G R A M')
      y = 0;
      return
    end
    current_String = fgetl(CalFile);
  end

  if strncmp(current_String, 'VAR_LIST_BEGIN', 14)
    %%%%%%%%%%%% Read the frequencies for VAR_LIST %%%%%%%%%%%%%
    text = sprintf('  Reading frequencies... \n');
    disp(text);
    FREQUENCY_counter = 0;
    Current_Frequency = fgetl(CalFile);
    while ~strncmp(Current_Frequency, 'VAR_LIST_END', 12)
      FREQUENCY_counter = FREQUENCY_counter + 1;
      Frequency_Array(FREQUENCY_counter,1) = str2num(Current_Frequency);
      Current_Frequency = fgetl(CalFile);
      if FREQUENCY_counter > 800
        disp('ERROR! The number of frequencies in the file is bigger than the maximum number for the HP8510 (801)')
        disp('E X I T  P R O G R A M')
        y = 0;
        return
      end
    end
    y = Frequency_Array;
  elseif strncmp(current_String, 'SEG_LIST_BEGIN', 14)
    %%%%%%%%%%%%% Read the frequencies for SEG_LIST %%%%%%%%%%%%%
    text = sprintf('  Reading frequencies... \n');
    disp(text);
    Current_Frequency = fgetl(CalFile);
    Right = Current_Frequency(4: size(Current_Frequency,2));
    frequency_range = str2num(Right);
    Frequency_Array = (frequency_range(1): (frequency_range(2) - frequency_range(1))/(frequency_range(3)-1): frequency_range(2));
    y = Frequency_Array';
    return
  else
    y = 0;
    return
  end
return

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FUNCTION: ReadErrorTerms(FileHandler, NumberOfFrequencies)                     %
% INPUT:    FileHeandler                                                         %
% OUTPUT:   Vektor (Frequency list read from indicated file)                     %
% AUTOR:    Tobias Werner, Universitaet Stuttgart                                %
% DATE:     February 29, 2000                                                    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function y = ReadErrorTerms(CalFile, NumberOfFrequencies)
  exit_counter = 1;
  while isempty(findstr(fgetl(CalFile), 'BEGIN'))
    exit_counter = exit_counter + 1;
    if exit_counter > 20
      disp('ERROR in file format!')
      disp('E X I T  P R O G R A M')
      return
    end
  end

  % Read the error terms for every frequency
  text = sprintf('  Reading error terms for %d frequencies... \n', NumberOfFrequencies);
  disp(text);
  ErrorTerm_counter = 0;
  Current_ErrorTerm = fgetl(CalFile);
  while isempty(findstr(Current_ErrorTerm, 'END'))
    ErrorTerm_counter = ErrorTerm_counter + 1;
    zahl = str2num(Current_ErrorTerm);
    zahl1 = zahl(:,1)+ i.*zahl(:,2);
    ErrorTerm_Array(ErrorTerm_counter,1) = zahl1;
    Current_ErrorTerm = fgetl(CalFile);
    if ErrorTerm_counter > NumberOfFrequencies
      disp('ERROR in file format!')
      disp('E X I T  P R O G R A M')
      y = 0;
      return
    end
  end
  y = ErrorTerm_Array;
return
```

```
%%%
```

```
%%%
```

Appendix G: MICROWAVE SWITCH CONTROL

The microwave setup is intended to characterize transistors on waver in the microwave frequency range from 2 GHz to 18 GHz, concerning S-parameters, power and noise. The system is also capable to measure DC-characteristics (I-V curves, etc.).

For each measurement type a different system configuration is necessary. This means, that different instruments have to be combined and as a result the sensitive connections have to be unscrewed and reconnected very often. The contact quality declines, this affects the repeatability of the contacts, and it is then required to perform a time-consuming system calibration as often as the configuration changes. Furthermore it is not possible to determine several properties of the same transistor without releasing the contacts between the microwave probes and the pads of the transistor. In case the transistor remains connected, vibrations can damage the device while the system configuration is altered.

To make measurement less time-consuming and to get rid of the mentioned disadvantages, the system was extended by two microwave switches.

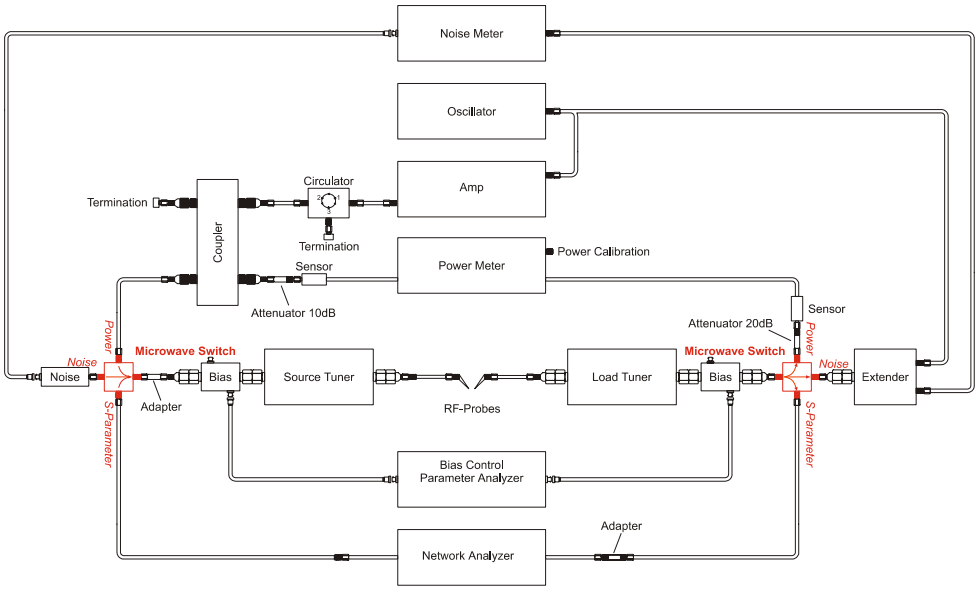


Fig. G.1: The new microwave setup to characterize DC-characteristics, S-parameters, power and noise of transistors in the microwave frequency range from 2 GHz to 18 GHz. Microwave switches at the input and output allow to switch between different setup configurations without having to calibrate the system again.

Fig. G.1 shows the changed setup with the microwave switches at the input and output of the system. If the entire setup is initially characterized, it is now possible to switch between S-parameter, power and noise measurement without having to disassemble or calibrate the system again. DC-measurements can be performed at any time independent of the selected measurement path. Measurements can now be carried out much quicker.

It was desirable to control the switches by software and to fully integrate it into the existing software tool of *Maury Microwaves*. For this purpose a system, consisting of hardware and software, was developed and will be discussed in the following chapters.

G.1 Microwave switches

Microwave switches from DowKey[10] were chosen, because of their superior RF characteristics and power handling capabilities, (*Table G.1*).

Frequency	VSWR	Isolation	Insertion Loss	RF Power
GHz	(max)	dB (min)	dB (max)	Watts (CW)
DC-4	1.25	70	0.20	100
4-8	1.35	65	0.30	70
8-12	1.40	60	0.40	60
12-18	1.50	60	0.50	45

Table G.1: RF properties of the used microwave switches.

A three way, normally-open switch model with the part number DowKey 535-520822A was selected, because the coil voltage was specified for 12 V and it was possible to control the switch with TTL compatible logic (5 V). The switch was equipped with SMA connectors and indicator contacts to reflect the currently selected path.

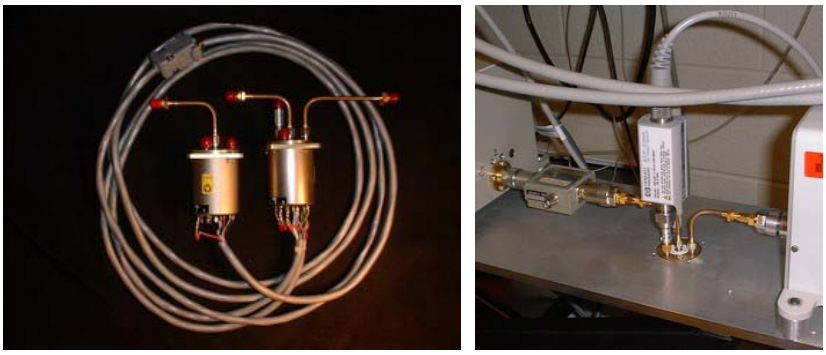


Fig. G.2: (left) The two microwave switches with indicator LEDs connected to the control cable. Rigid microwave cables at the inputs and outputs are mounted to connect to the system components. (right) A mounted microwave switch on the load side of the system.

[10] DowKey Microwave Corporation, 1667 Walter Street, Ventura, California 93003, USA, PHONE (805) 650-0260 • FAX (805) 650-1734

G.2 Hardware

In general, computers provide supply voltages of +12V and +5 V for the main board and additional devices. Therefore, the microwave switch control was designed to use as well the computer supply to power the microwave switches.

The parallel port (LPT) of a computer uses TTL compatible[11] voltages and is thus able to send control information to the switch.

Unfortunately, the Maury Software ATS[12] is protected against illegal copies by a hardware key at the parallel port.

The following subchapters describe the hardware, designed to prevent from interaction between the hardware key and the control commands, intended for the microwave switch.

G.2.1 Schematic

The hardware key itself passes all signals from the input to the output. To control a microwave switch, a positive voltage of 5 V has to be sent to one of its three TTL ports to activate the normally opened corresponding signal path. The switch only accepts a single high level at one of the three TTL ports and must be protected against unsuited signals. This is what the circuit is intended for.

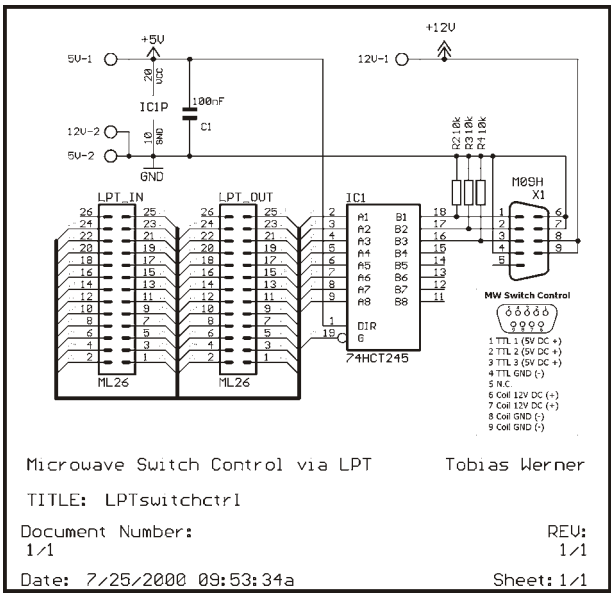


Fig. G.3: The schematic of the microwave switch control.

[11] High: +2.0 V to +5.2 V, Low: 0 V to +0.8 V

[12] Automated Tuner System

The heart of the schematic shown in *Fig. G.3* is the 74HCT245, a 3-state octal bus transceiver. In the selected configuration, it passes the data (byte) at port A to Port B, if the enable port G is activated (low active).

The connector labeled LPT_IN receives the parallel port signal from the motherboard and passes it directly to the LPT port on the rear of the computer via the connector labeled LPT_OUT. The data byte of the parallel port signal is also passed to the transceiver data input ports. The printer enable signal (*nSelect-Printer*) is connected to the enable port G of the transceiver and activates the setting of the microwave switches.

The port assignment of the parallel port and corresponding signal name is outlined in *Table G.2*.

Pin No (D-Type)	Pin No (main board)	Pin No (Centronics)	SPP Signal	Direction In/out	Register	Hardware Inverted
1	1	1	nStrobe	In/Out	Control	Yes
2	3	2	Data 0	Out	Data	
3	5	3	Data 1	Out	Data	
4	7	4	Data 2	Out	Data	
5	9	5	Data 3	Out	Data	
6	11	6	Data 4	Out	Data	
7	13	7	Data 5	Out	Data	
8	15	8	Data 6	Out	Data	
9	17	9	Data 7	Out	Data	
10	19	10	nAck	In	Status	
11	21	11	Busy	In	Status	Yes
12	23	12	Paper-Out / Paper-End	In	Status	
13	25	13	Select	In	Status	
14	2	14	nAuto-Linefeed	In/Out	Control	Yes
15	4	32	nError / nFault	In	Status	
16	6	31	nInitialize	In/Out	Control	
17	8	36	nSelect-Printer / nSelect-In	In/Out	Control	Yes
18	10	19	Ground	Gnd		
19	12	20	Ground	Gnd		
20	14	21	Ground	Gnd		
21	16	22	Ground	Gnd		
22	18	23	Ground	Gnd		
23	20	24	Ground	Gnd		
24	22	25	Ground	Gnd		
25	24	26	Ground	Gnd		
-	26 (NC)	27	Ground	Gnd		
-	-	28	Ground	Gnd		
-	-	29	Ground	Gnd		
-	-	30	Ground	Gnd		

Table G.2: Parallel port (LPT) assignment and signal names.

Only the three least significant bits of the parallel port signal are utilized to control the position of the switch. *Table G.3* shows which one of the three possible signal paths is connected to the common contact, depending on the data byte and the enable port G state.

Enable port G	Data byte	Connected signal path
0	xxxx x001	Common with port 1
0	xxxx x010	Common with port 2
0	xxxx x100	Common with port 3
0	xxxx x000	No port connected to common
1	xxxx xxxx	No port connected to common

Table G.3: Control settings and the relating activated signal path of the microwave switch.

To protect the bus transceiver from oscillations in the supply voltage, a 100 nF capacitor is applied.

The output ports of the transceiver are three state ports, i.e. the port can be high (5 V), low (GND) or can be in a high ohmic state. To guarantee a proper voltage level in the latter case, according to the TTL definition, pull-down resistors are connected to the outputs of the transceiver.

The control signals and the 12 V coil supply voltage are interfaced by a female 9-pin sub D connector by which it can be easily mounted inside a standard PC enclosure.

G.2.2 Layout

The layout and schematic was developed with an educational version of Eagle V3.55r3 of CadSoft. The layout from the component view of the microwave switch control and the placement of the components can be seen in *Fig. G.4*.

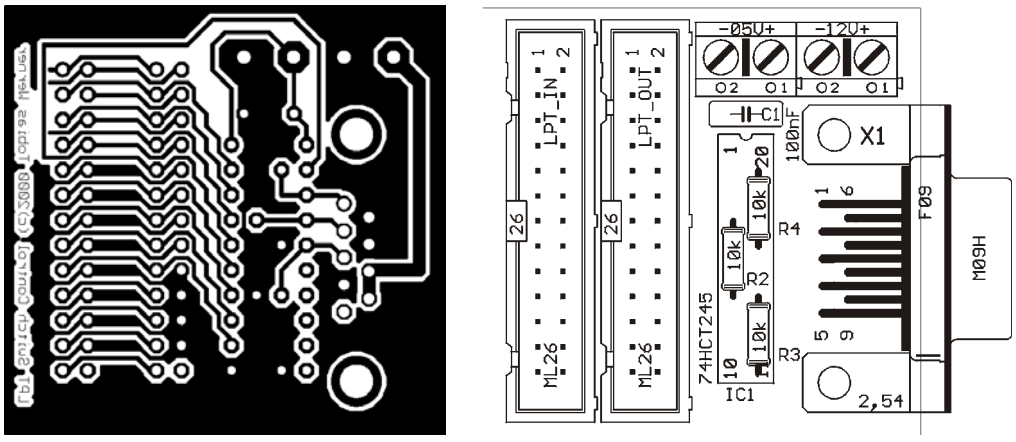


Fig. G.4: The layout (left) and the component placement (right) of the microwave switch control.

In the left most part of the circuit board, the two connectors used to pass and access the parallel port signal. In the middle the transceiver circuit, above it the block capacitor and underneath, to save space, the three pull down resistors. In the upper right area the two connectors for the power supply and on the right most side the female 9-pin sub D connector.

G.2.3 Printed circuit board

Fig. G.5 illustrates the technical realization of the printed circuit board from the component and the solder side.

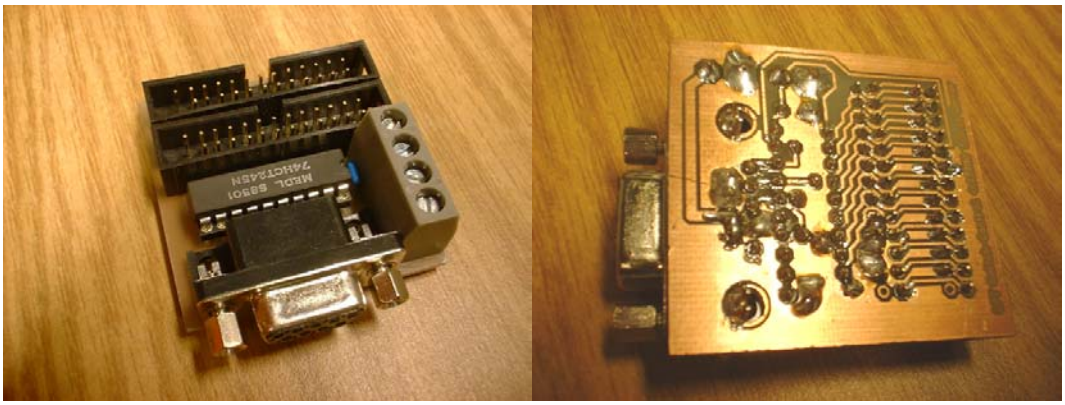


Fig. G.5: Top and bottom view of the printed circuit board to control the microwave switches.

G.3 Software

The program to control the hardware via the parallel port of the computer was written in Microsoft Visual C++ 6.0. *Fig. G.6* shows the user interface of the program.

The microwave measurement setup can be switched to the three configurations, S-parameter, Power and Noise or can be turned offline; in this case no signal path is activated.

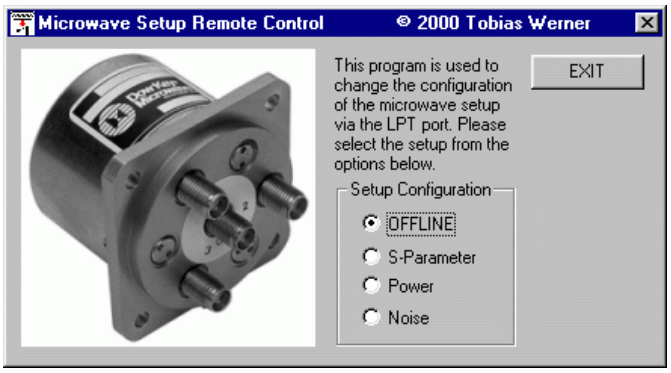

Microwave Setup Remote Control
© 2000 Tobias Werner
This program is used to change the configuration of the microwave setup via the LPT port. Please select the setup from the options below.
EXIT
Setup Configuration
OFFLINE
S-Parameter
Power
Noise

Fig. G.6: The user interface to control the microwave switches.

G.3.1 Program code

In the following the source code with all functions can be found.

G.3.1.1 Header file: LPTSwitchRemote.h

```
// LPTSwitchRemote.h : main header file for the LPTSWITCHREMOTE application
//
#if !defined(AFX_LPTSWITCHREMOTE_H__0BD27EC4_5C15_11D4_B354_0006295283FA__INCLUDED_)
#define AFX_LPTSWITCHREMOTE_H__0BD27EC4_5C15_11D4_B354_0006295283FA__INCLUDED_
#if _MSC_VER > 1000
#pragma once
#endif // _MSC_VER > 1000
#ifndef __AFXWIN_H__
  #error include 'stdafx.h' before including this file for PCH
#endif
#include "resource.h"   // main symbols

/////////////////////////////////////////////////////////////////////////////
// CLPTSwitchRemoteApp:
// See LPTSwitchRemote.cpp for the implementation of this class
//
class CLPTSwitchRemoteApp : public CWinApp
{
public:
  CLPTSwitchRemoteApp();
// Overrides
  // ClassWizard generated virtual function overrides
  //{{AFX_VIRTUAL(CLPTSwitchRemoteApp)
  public:
  virtual BOOL InitInstance();
  //}}AFX_VIRTUAL
// Implementation
  //{{AFX_MSG(CLPTSwitchRemoteApp)
    // NOTE - the ClassWizard will add and remove member functions here.
    //    DO NOT EDIT what you see in these blocks of generated code !
  //}}AFX_MSG
  DECLARE_MESSAGE_MAP()
};
/////////////////////////////////////////////////////////////////////////////
//{{AFX_INSERT_LOCATION}}
// Microsoft Visual C++ will insert additional declarations immediately before the previous line.
#endif // !defined(AFX_LPTSWITCHREMOTE_H__0BD27EC4_5C15_11D4_B354_0006295283FA__INCLUDED_)
```

G.3.1.2 Header file: LPTSwitchRemoteDlg.h

```
// LPTSwitchRemoteDlg.h : header file
//
#if !defined(AFX_LPTSWITCHREMOTEDLG_H__0BD27EC6_5C15_11D4_B354_0006295283FA__INCLUDED_)
#define AFX_LPTSWITCHREMOTEDLG_H__0BD27EC6_5C15_11D4_B354_0006295283FA__INCLUDED_
#if _MSC_VER > 1000
#pragma once
#endif // _MSC_VER > 1000
/////////////////////////////////////////////////////////////////////////////
// CLPTSwitchRemoteDlg dialog

class CLPTSwitchRemoteDlg : public CDialog
{
// Construction
public:
  UINT GetLPTPortBaseAddress(int PortNumber);
```

```
  int ControlOutput(int SendByte);
  int ReadPortStatus();
  CLPTSwitchRemoteDlg(CWnd* pParent = NULL);      // standard constructor

// Dialog Data
  //{{AFX_DATA(CLPTSwitchRemoteDlg)
  enum { IDD = IDD_LPTSWITCHREMOTE_DIALOG };
  int   m_SetupConfig;
  //}}AFX_DATA
  // ClassWizard generated virtual function overrides
  //{{AFX_VIRTUAL(CLPTSwitchRemoteDlg)
  protected:
  virtual void DoDataExchange(CDataExchange* pDX); // DDX/DDV support
  //}}AFX_VIRTUAL

// Implementation
protected:
  HICON m_hIcon;
  // Generated message map functions
  //{{AFX_MSG(CLPTSwitchRemoteDlg)
  virtual BOOL OnInitDialog();
  afx_msg void OnSysCommand(UINT nID, LPARAM lParam);
  afx_msg void OnPaint();
  afx_msg HCURSOR OnQueryDragIcon();
  afx_msg void OnExit();
  afx_msg void OnChangeConfig();
  //}}AFX_MSG
  DECLARE_MESSAGE_MAP()
};

//{{AFX_INSERT_LOCATION}}
// Microsoft Visual C++ will insert additional declarations immediately before the previous line.
#endif // !defined(AFX_LPTSWITCHREMOTEDLG_H__0BD27EC6_5C15_11D4_B354_0006295283FA__INCLUDED_)
```

G.3.1.3 Implementation file: LPTSwitchRemote.cpp

```
// LPTSwitchRemote.cpp : Defines the class behaviors for the application.
//

#include "stdafx.h"
#include "LPTSwitchRemote.h"
#include "LPTSwitchRemoteDlg.h"
#ifdef _DEBUG
#define new DEBUG_NEW
#undef THIS_FILE
static char THIS_FILE[] = __FILE__;
#endif

/////////////////////////////////////////////////////////////////////////////
// CLPTSwitchRemoteApp

BEGIN_MESSAGE_MAP(CLPTSwitchRemoteApp, CWinApp)
  //{{AFX_MSG_MAP(CLPTSwitchRemoteApp)
    // NOTE - the ClassWizard will add and remove mapping macros here.
    //    DO NOT EDIT what you see in these blocks of generated code!
  //}}AFX_MSG
  ON_COMMAND(ID_HELP, CWinApp::OnHelp)
END_MESSAGE_MAP()

/////////////////////////////////////////////////////////////////////////////
// CLPTSwitchRemoteApp construction

CLPTSwitchRemoteApp::CLPTSwitchRemoteApp()
{
  // TODO: add construction code here,
  // Place all significant initialization in InitInstance
}

/////////////////////////////////////////////////////////////////////////////
// The one and only CLPTSwitchRemoteApp object

CLPTSwitchRemoteApp theApp;

/////////////////////////////////////////////////////////////////////////////
// CLPTSwitchRemoteApp initialization

BOOL CLPTSwitchRemoteApp::InitInstance()
{
  // Standard initialization
  // If you are not using these features and wish to reduce the size
  //  of your final executable, you should remove from the following
  //  the specific initialization routines you do not need.

#ifdef _AFXDLL
  Enable3dControls();     // Call this when using MFC in a shared DLL
#else
  Enable3dControlsStatic(); // Call this when linking to MFC statically
#endif

  CLPTSwitchRemoteDlg dlg;
  m_pMainWnd = &dlg;
  int nResponse = dlg.DoModal();
  if (nResponse == IDOK)
  {
    // TODO: Place code here to handle when the dialog is
    //  dismissed with OK
  }
  else if (nResponse == IDCANCEL)
  {
    // TODO: Place code here to handle when the dialog is
    //  dismissed with Cancel
  }

  // Since the dialog has been closed, return FALSE so that we exit the
  //  application, rather than start the application's message pump.
  return FALSE;
}
```

G.3.1.4 Implementation file: LPTSwitchRemoteDlg.cpp

```
// LPTSwitchRemoteDlg.cpp : implementation file
//

#include "stdafx.h"
#include "LPTSwitchRemote.h"
#include "LPTSwitchRemoteDlg.h"
#include <conio.h>
#include <dos.h>

#ifdef _DEBUG
#define new DEBUG_NEW
#undef THIS_FILE
static char THIS_FILE[] = __FILE__;
#endif

# define LPT1       0x378   //lpt1
# define STATUS       LPT1 + 1//lpt1
# define CONTROL    LPT1 + 2//lpt1
# define ERROR      0
# define SUCCESS    1
# define SWITCH_ENABLE  236 // 11101100
# define SWITCH_DISABLE   228 // 11100100
# define SWITCH_OFFLINE   000 //DB0,DB1,DB2,DB3,DB4,DB5,DB6,DB7=high 255
# define SWITCH_S_PARAMETER 001 //DB0=low, DB1,DB2,DB3,DB4,DB5,DB6,DB7=high 254
# define SWITCH_POWER   002 //DB1=low, DB0,DB2,DB3,DB4,DB5,DB6,DB7=high 253
# define SWITCH_NOISE   004 //DB2=low, DB0,DB1,DB3,DB4,DB5,DB6,DB7=high 251
//# define LPT2 0x278 //lpt2
CString MessageControlString;
/////////////////////////////////////////////////////////////////////////////
// CAboutDlg dialog used for App About

class CAboutDlg : public CDialog
{
public:
  CAboutDlg();

// Dialog Data
  //{{AFX_DATA(CAboutDlg)
  enum { IDD = IDD_ABOUTBOX };
  //}}AFX_DATA

  // ClassWizard generated virtual function overrides
  //{{AFX_VIRTUAL(CAboutDlg)
  protected:
  virtual void DoDataExchange(CDataExchange* pDX);    // DDX/DDV support
  //}}AFX_VIRTUAL

// Implementation
protected:
  //{{AFX_MSG(CAboutDlg)
  //}}AFX_MSG
  DECLARE_MESSAGE_MAP()
};

CAboutDlg::CAboutDlg() : CDialog(CAboutDlg::IDD)
{
  //{{AFX_DATA_INIT(CAboutDlg)
  //}}AFX_DATA_INIT
}

void CAboutDlg::DoDataExchange(CDataExchange* pDX)
{
  CDialog::DoDataExchange(pDX);
  //{{AFX_DATA_MAP(CAboutDlg)
  //}}AFX_DATA_MAP
}

BEGIN_MESSAGE_MAP(CAboutDlg, CDialog)
  //{{AFX_MSG_MAP(CAboutDlg)
    // No message handlers
  //}}AFX_MSG_MAP
END_MESSAGE_MAP()

/////////////////////////////////////////////////////////////////////////////
// CLPTSwitchRemoteDlg dialog

CLPTSwitchRemoteDlg::CLPTSwitchRemoteDlg(CWnd* pParent /*=NULL*/)
  : CDialog(CLPTSwitchRemoteDlg::IDD, pParent)
{
  //{{AFX_DATA_INIT(CLPTSwitchRemoteDlg)
  m_SetupConfig = -1;
  //}}AFX_DATA_INIT
  // Note that LoadIcon does not require a subsequent DestroyIcon in Win32
  m_hIcon = AfxGetApp()->LoadIcon(IDR_MAINFRAME);
}

void CLPTSwitchRemoteDlg::DoDataExchange(CDataExchange* pDX)
{
  CDialog::DoDataExchange(pDX);
  //{{AFX_DATA_MAP(CLPTSwitchRemoteDlg)
  DDX_Radio(pDX, IDC_RADIO_OFFLINE, m_SetupConfig);
  //}}AFX_DATA_MAP
}

BEGIN_MESSAGE_MAP(CLPTSwitchRemoteDlg, CDialog)
  //{{AFX_MSG_MAP(CLPTSwitchRemoteDlg)
  ON_WM_SYSCOMMAND()
  ON_WM_PAINT()
  ON_WM_QUERYDRAGICON()
  ON_BN_CLICKED(IDB_EXIT, OnExit)
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  ON_BN_CLICKED(IDC_RADIO_POWER, OnChangeConfig)
  ON_BN_CLICKED(IDC_RADIO_NOISE, OnChangeConfig)
```

```
  //}}AFX_MSG_MAP
END_MESSAGE_MAP()

/////////////////////////////////////////////////////////////////////////////
// CLPTSwitchRemoteDlg message handlers

BOOL CLPTSwitchRemoteDlg::OnInitDialog()
{
  CDialog::OnInitDialog();

  // Add "About..." menu item to system menu.

  // IDM_ABOUTBOX must be in the system command range.
  ASSERT((IDM_ABOUTBOX & 0xFFF0) == IDM_ABOUTBOX);
  ASSERT(IDM_ABOUTBOX < 0xF000);

  CMenu* pSysMenu = GetSystemMenu(FALSE);
  if (pSysMenu != NULL)
  {
    CString strAboutMenu;
    strAboutMenu.LoadString(IDS_ABOUTBOX);
    if (!strAboutMenu.IsEmpty())
    {
      pSysMenu->AppendMenu(MF_SEPARATOR);
      pSysMenu->AppendMenu(MF_STRING, IDM_ABOUTBOX, strAboutMenu);
    }
  }

  // Set the icon for this dialog.  The framework does this automatically
  //  when the application's main window is not a dialog
  SetIcon(m_hIcon, TRUE);     // Set big icon
  SetIcon(m_hIcon, FALSE);  // Set small icon
//UINT PortBaseAdress;
//PortBaseAdress = GetLPTPortBaseAddress(1);

  m_SetupConfig = ReadPortStatus();
  UpdateData(false);
  // TODO: Add extra initialization here

  return TRUE;  // return TRUE  unless you set the focus to a control
}

void CLPTSwitchRemoteDlg::OnSysCommand(UINT nID, LPARAM lParam)
{
  if ((nID & 0xFFF0) == IDM_ABOUTBOX)
  {
    CAboutDlg dlgAbout;
    dlgAbout.DoModal();
  }
  else
  {
    CDialog::OnSysCommand(nID, lParam);
  }
}

// If you add a minimize button to your dialog, you will need the code below
//  to draw the icon.  For MFC applications using the document/view model,
//  this is automatically done for you by the framework.

void CLPTSwitchRemoteDlg::OnPaint()
{
  if (IsIconic())
  {
    CPaintDC dc(this); // device context for painting

    SendMessage(WM_ICONERASEBKGND, (WPARAM) dc.GetSafeHdc(), 0);

    // Center icon in client rectangle
    int cxIcon = GetSystemMetrics(SM_CXICON);
    int cyIcon = GetSystemMetrics(SM_CYICON);
    CRect rect;
    GetClientRect(&rect);
    int x = (rect.Width() - cxIcon + 1) / 2;
    int y = (rect.Height() - cyIcon + 1) / 2;

    // Draw the icon
    dc.DrawIcon(x, y, m_hIcon);
  }
  else
  {
    CDialog::OnPaint();
  }
}

// The system calls this to obtain the cursor to display while the user drags
//  the minimized window.
HCURSOR CLPTSwitchRemoteDlg::OnQueryDragIcon()
{
  return (HCURSOR) m_hIcon;
}

int CLPTSwitchRemoteDlg::ReadPortStatus()
{
  //possible: 1,2,4 low active!
  int ControlByte;
  int DataByte;
  int OptionSetting;

  ControlByte = _inp(CONTROL);
  if(ControlByte == SWITCH_DISABLE)
  {
    OptionSetting = 0;
  }
  else
  {
    DataByte = _inp(LPT1);
    switch(DataByte)
    {
    case 255:
      OptionSetting = 0;
      break;
```

```
    case 254:
      OptionSetting = 1;
      break;
    case 253:
      OptionSetting = 2;
      break;
    case 251:
      OptionSetting = 3;
      break;
    default:
      _outp(LPT1,SWITCH_OFFLINE);
      OptionSetting = _inp(LPT1);
      if(OptionSetting != SWITCH_OFFLINE)
      {
        MessageControlString.Format("An error occured! Wrong data (%d) was read from LPT1!",OptionSetting);
        MessageBox(MessageControlString);
      }
    }
  }
  return(OptionSetting);
}

void CLPTSwitchRemoteDlg::OnChangeConfig()
{
  int SendByte = 0;
  UpdateData(true);
  switch(m_SetupConfig)
  {
  case 1: // S-parameter setup selected
    SendByte = SWITCH_S_PARAMETER;
    break;
  case 2: // Power setup selected
    SendByte = SWITCH_POWER;
    break;
  case 3: // Noise setup selected
    SendByte = SWITCH_NOISE;
    break;
  default: // Switches turned off
    SendByte = SWITCH_OFFLINE;
    break;
  }
  _outp(LPT1, SendByte); // sends byte to port lpt1
  _outp(CONTROL,SWITCH_ENABLE); //enable nPrSel => send bin1111100 => low active: Pin3=low!
  //check if changes were reflected!
  if(ControlOutput(SendByte) == ERROR)
  {
    _outp(CONTROL,SWITCH_DISABLE); //disable nPrSel => send bin1110100 => low active: Pin3=high!
  }
}

void CLPTSwitchRemoteDlg::OnExit()
{
  // if exit program => set port disabled

  // set LPT data ports to disabled
  _outp(LPT1,SWITCH_OFFLINE); //set all high = LOWACTIVE 0

  // set LPT control ports to disabled
  _outp(CONTROL,SWITCH_DISABLE); //disable nPrSel default = bin1110100 (dec228)

  // if switches were not yet turned offline manually,
  // display message
  if(m_SetupConfig!=0)
    MessageBox("Switches turned OFFLINE.");
  CDialog::OnOK();
}


int CLPTSwitchRemoteDlg::ControlOutput(int SendByte)
{
  int ReadByte;

  ReadByte = _inp(LPT1);
  if(ReadByte != SendByte)
  {
    MessageBox("ERROR setting switch!");
    return(ERROR);
  }
  else
  {
    switch(ReadByte)
    {
    case SWITCH_S_PARAMETER: // S-Parameter
      MessageBox("Switched to S-PARAMETER configuration!");
      break;
    case SWITCH_POWER: // Power
      MessageBox("Switched to POWER configuration.");
      break;
    case SWITCH_NOISE: // Noise
      MessageBox("Switched to NOISE configuration.");
      break;
    case SWITCH_OFFLINE: // Switches turned off
      MessageBox("Switches turned OFFLINE.");
      break;
    default :
      MessageBox("Wrong argument in modul ControlOutput!");
      return(ERROR);
    }
    return(SUCCESS);
  }
}


UINT CLPTSwitchRemoteDlg::GetLPTPortBaseAddress(int PortNumber)
{
  //return *((unsigned int far *)MK_FP(0x40, 6) + 2 * PortNumber);
  return 0;
}
```

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